THE DESIGN AND PERFORMANCE OF SOLID STATE REVERSIBLE D. C. MOTOR DRIVE

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by
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CERTIFICATE

Certified that this work, 'The Design And Performance Of Solid State Reversible D.C. Drive' by S.R. Nigam is carried under my supervision and is not submitted for a degree elsewhere.

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ABSTRACT

The thesis describes the design of non circulating current dual converters scheme for separately excited D.C. Motor. The design of speed loop and current loop, PI and proportional controllers along with electronic circuitry involved is also discussed. The experimental model developed in lab includes following features.

i) Reversing

ii) Inching

iii) Jogging

iv) Acceleration control

The experimental and theoritical results for Dynamic and steady state performance of the system, under various condition of feedback and loading are given.

CONTENTS

CHAPTER I

INTRODUCTION

1.1 Many processes in present day technology require variable speed drives. On the past the most widely used system was'ward Leonard' system of speed control, using motor-generator set. Because of this the drive use to occupy lot of floor area and require frequent maintenance. This system was having large inertia and losses inherent to machines. Therefore, the drive was sluggish and less efficient. Now with the advant of 'silicon controlled rectifiers' (SCRs) it is possible, very conveniently to supply direct current to D.C. motors at variable voltage. There are two basic methods where by variable D.C. voltage can be supplied to the motor; (1) using a controlled rectifier bridge supplied from a single phase or three phase A.C. supply; (2) using a chopper supplied from constant voltage D.C. supply. The first method is usually used whenever A.C. power can be made available like A.C. driven industrial drives. The second method is used when the power source is a battery or D.C. A detailed description of these methods are given later.

Apart from speed control there are some other requirements by industry such as :

(i) Inching

(ii) Jogging

(iii) Reversing

(iv) Braking

(v) Acceleration and retardation control

(vi) Overload Protection

(vii) Constant horse power operation

(viii) Constant torque operation

(ix) Load sharing

(x) Emergency stop

(xi) Regulation on speed

With electronic control it is easy to incorporate these additional specifications in the drive system. A brief explanation of these terms is given below :

(i) Inching :

Movement of the machine shaft by a fraction of a revolution, i.e. rotating the shaft by few inches. This operation is desirable to position the load.

(ii) Jogging :

It means that machine should rotate at very low speed say below 20 RPM. This limit is not fixed but depends on the requirement.

(iii) Reversing :

Many times it is required to reverse the speed of motor. This can be done by reversing the polarity of

armature voltage or field supply. Because of the large field inductance the time taken to reverse the motor speed will be more and depends on the field forcing while the reversal of armature supply results in quick reversal of speed.

This polarity change over can be achieved by change over contactors or by using dual AC/DC converters. Again the contactors take more time (nearly 50 ms or more) than dual converters. But the dual converters cost more. Dual converters scheme can be further subdivided in to two (a) non-circulating current (b) circulating current scheme.

(a) Non-circulating current scheme :

Here one bridge is fired at a time. Whenever reversal is desired the firing pulses are stopped to conducting bridge. The current is monitered, as soon as current becomes zero the firing pulses are given to another bridge conducting in reverse direction. Because we have to wait for current zero this scheme will require more time compared to the other scheme discussed below.

(b) Circulating current scheme :

In this scheme both the bridges are fired simultaneously one working as rectifier and the other as inverter. Whenever reversal is desired the inverting bridge is made to operate

as rectifier by reducing its firing angle 'α' while rectifying bridge is made inverter by firing it at $(\pi-\alpha)$. This reversal is quite fast and requires only 10 ms to change over, However, the scheme has the disadvantage of large circulating current between the two bridges. To limit this current a reactor is to be used. Because it has to carry direct current the cost and size is considerable.

In the process of reversing, it is first required to brake the motor and then accelerate in reverse direction. The process of braking is discussed under separate heading.

(iv) Braking :

For quick stopping of rotation some form of braking is required. Mechanical or frictional braking involves lot of heat dissipation. There are three types of Electrical braking.

(a) Dynamic braking
(b) Plugging
(c) Regenerative braking

A brief description of these are given below :

(a) Dynamic braking :

Here the supply is disconnected from armature and the armature is connected to a resistance. The Kinetic energy of the system is dissipated as heat in resistance and motor works

as generator. This method is not quite fast but can be used upto very low speed of machine. If the system is of large inertia a considerable amount of energy may be wasted which gives rise to low over all efficiency if frequent stopping is called for.

(b) Plugging :

Here the supply is reversed and the energy is dissipated as heat inside the motor it self. However, armature current is to be limited by advancing the firing angle 'α' during braking so that it does not exceed the safe value. This system is faster but for large inertia system might not be suitable as the motor may have large temperature rise,

(c) Regenerative braking :

In this scheme the kinetic energy of the system is fed back to supply and therefore happens to be economical and fast. But it can not be applied for low speeds. As the circuit required for this scheme is expensive it may not be a proper choise for low HP systems. The supply must be able to absorb the extra Electrical energy generated without causing over shoot to system voltage. This calls for some other load on the supply at that instant. This form of braking

is preferable for traction. In several cases regenerative braking is used until the speed falls to about 50 percent of the initial speed and plugging or dynamic braking is used from 50 percent to about 15 percent. This speed range is used in particular for traction. Then frictional braking is employed (electrical or mechanical) at lower speed.

(v) Acceleration control :

Some time it is desired to control acceleration or retardation. Because it depends on the amount of torque generated by motor, by control of armature current it is possible to control the acceleration. The armature current is limited by retarding or advancing the firing angle 'α'.

(vi) Over load protection :

The current supplied by SCRs must not exceed a safe limit. As the thermal capacity of SCRs is not good. For this we provide fast acting fuses and current limiting circuits. The current limiting circuit may be same as for acceleration control.

(vii) Constant horse power operation :

This characteristic is desirable for traction at high speed or for variable torque loads. Here the constrain on armature current is removed except for maximum safe limit.

The armature current is allowed to adjust automatically as the system demands. Speed variations achieved by field control.

(viii) Constant Torque Operation :

Because for D.C. motors the torque generated is proportional to the product of airgap flux and armature current if armature current for series motors and field current and armature current for separately excited motors are kept constant the torque will be constant. For both of the motors the armature current is maintained constant at desired level. The current feed back by current transformer or a torque transducer can be used. However, torque transducers, though expensive, give more precise control than current transformers.

This operation is desired for reeling process in paper and wire drawing industry. With current control and speed feed back the characteristics of the drive system is such that the developed torque is maintained constant.

(ix) Load Sharing :

If more than one motor is to drive a load like in trains, it is necessary to see that no motor is overloaded. Here we can compare the current drawn by all motors and adjust the firing angle.

(x) Emergency Stopping :

If due to some emergency it is required to stop the motor usually a heavy dynamic braking is applied.

(xi) Regulation on Speed :

If it is desired to have zero steady state speed error a proportional integral (PI) controller can be used. If some speed regulation with load is tolerable a proportional controller can be used (For step input). Also the speed regulation depends on the type of transducer used. If a techogenerator is used it is possible to achieve a regulation of less than 0.5 percent while with armature voltage feed back with IR compensation it is possible to achieve a regulation of 2 to 5 percent. Depending upon the requirement and cost the combination is picked up.

All the above listed operations are very conveniently possible with thyristors drives. They are now replacing the motor-generator sets.

In short we can compare the D.C. motor speed control with motor generator set as follows :

(a) With the elimination of large system time constants stability is not a problem even with high closed loop gains. A fast response system can then be designed with a transient and steady state accuracy limited only by the quality of the process transducer.

(b) By the use of integrated circuits it is possible to incorporate any desired logic and type of controllers, with highest reliability and accuracy.

(c) Consisting of only a D.C. motor and control cubicle, the latter for example, being only 75 cm x 75 cm x 200 cm for a 150 H.P. drive, the floor space and foundation requirements are at a minimum.

(d) A wide efficient range of control down to zero output with controlled output rate and automatic torque limiting is possible.

(e) Negligible maintainance is required for SCR drives as the equipment is static.

(f) But it lacks the overload capacity due to the low thermal capacity of thyristors.

(g) These drives inject some harmonics in supply thereby distorting the supply. This is a serious problem for large H.P. drives, and special input filters must be employed.

(h) Converters take the current at logging power factor. Hence large systems may need some shunt capacitors to improve the input power factor.

We can classify the variable speed drives as (i) A.C. drives, (ii) D.C. drives.

(i) Because of SCRs it is now possible conveniently to control the speed of all types of A.C. motors i.e. induction motor, synchronous motor, reluctance motor or hysterisis motor. However, it is not the subject matter for this thesis hence will not be discussed here.

(ii) D.C. motor speed control : D.C. motors are ideally suited for variable speed drives. The control system is simple. Therefore, the D.C. motor solid state drives are quite popular in industry even though cost of D.C. motor is more
of same rating.
than the an A.C. motor. The D.C. drive can be further sub-divided into series motor speed control and separately excited motor speed control. To vary the speed of series motor the only way is to change the supply potential applied to motor. Because of the large field inductance, for a series motor the input current is continuous for all speeds. Hence it is not necessary to have any external series inductor. The speed control of separately excited motor can be achieved either by changing the armature voltage or field voltage. Because field has got high inductance the system will be sluggish. Also the quick reversals are not possible. However, the field current is always much less than armature current. Therefore, the cost of equipment is less. With armature supply control it is possible to have a fast system, hence

quick reversals. But here one has to control large amount of current compared to field current hence the cost is more. For higher power drives the field current control is preferred over armature supply control, because of saving in capital cost.

In all these method supply voltage (average) is to be changed for controlling the speed of D.C. motors. There are two ways to achieve it. (i) Using choppers, (ii) Using AC/DC converters.

(i) Choppers :

These are DC/DC converters. A DC supply is given to them. By varying the ratio of on to on+off time the average voltage supplied is changed. Both step up and step down chopper circuits are available. However, they require commutating elements and therefore are more costly, and less efficient than converters. The choppers do not suffer from the disadvantage of low power factor. If D.C. supply is given to chopper by rectifying the AC supply it is not possible to have a regenerativ braking if no other load is connected to DC bus. With the other load connected to DC bus it is possible to have two quadrant chopper operatin. choppers are now mostly used for traction by rails with overhead D.C. supply, and for battery operated vehicleS.

(ii) AC/DC Converters :

They are known as line commutated converters. Because the switching off of thyristors is done by line. They do not require any extra commutating elements. There are many variations available in the converter circuit. To enlist some of the important variations :

(i) Two pulse, three pulse or six pulse converters.
(ii) Bridge or mid point connection.
(iii) Fully controlled or half controlled bridges.

There are relative advantages and disadvantages to these variations. For motors above 5 H.P. the power has to be drawn from three phase supply hence three or higher pulses converters are the proper choise. With increase in no. of phases (pulses) the ripples in DC output become less. Hence it is preferable to use more No. of phases, where ever possible. But the cost is also higher because more No. of SCRs are to be used. For motors less than 3 H.P. two pulse converters are used because of cost reduction tolerating more ripples.

Mid point connection requires center tapped transformer, which is a costly item. Hence as far as possible it is avoided, so bridge connection is usual choice.

Because the half controlled bridge uses half the No. of SCRs and half the diodes compared to fully controlled bridge, the half controlled bridge is cheaper. However, regenerative braking is not possible by half controlled bridge, therefore in such places fully controlled bridge is essential. Free wheeling diode is not required with half controlled bridge, as it free wheels by itself but can be used with fully controlled bridge if reversal is not desired.

Depending upon the requirement of drive and type of load it is possible to choose among the various alternatives available.

This thesis is concerned with the design of a speed control system for a 0.5 H.P. separately excited motor. A fully controlled, single phase, non circulating current dual converter system is used to provide reversible drive with the following features.

(i) Inching

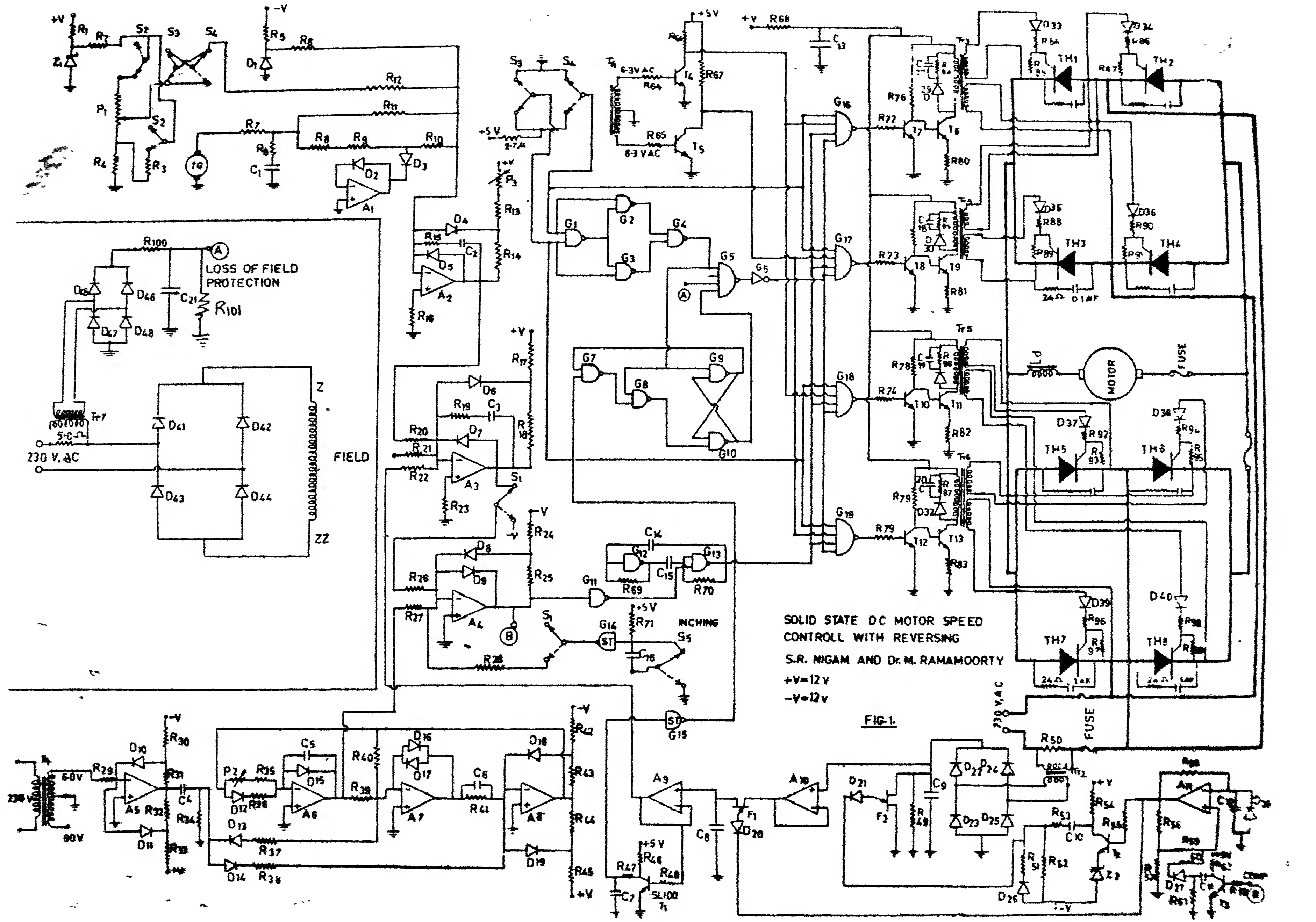
(ii) Jogging

(iii) Braking by plugging

(iv) Reversing

(v) Acceleration and retardation control.

The system's dynamic and steady state behaviour with open loop, proportional controller for speed with and without current feed back, proportional integeral controller with and without current feed back under the frictional and constant torque load is studied. The system description, controller design and the performance characteristics are reported in the following report.


SOLID STATE DC MOTOR SPEED
CONTROLL WITH REVERSING
S.R. NIGAM AND Dr. M. RAMAMOORTY
+V=12 V
-V=12 V
LOSS OF FIELD PROTECTION
FIELD
230 V. AC
MOTOR
FUSE
INCHING
230 V.A.C
FIG-1.

CHAPTER II

DESIGN OF POWER AND LOGIC CIRCUIT

2.1 Introduction

As indicated in Chapter 1, this thesis is devoted to speed control of D.C. separately excited motor with following features, (i) Inching, (ii) Jogging, (iii) Reversing, (iv) Acceleration control.

A 0.5 H.P. D.C. motor, with following ratings is used :

(i) Armature current	-	2.0 A
(ii) Field current	-	0.5 A
(iii) voltage	-	230 V
(iv) Speed (max)	-	1500 RPM

Two similar motors (one is to be used as load), along with a D.C. techogenerator were coupled together mechanically. The techogenerator develops 10.0 V at 1500 RPM when its field is supplied by 12 V D.C. supply. The various motor parameters useful for design and analysis were measured experimently as discussed in Appendix 'A'.

2.2 Design of Converter

Since the motor to be controlled is only of 0.5 H.P. from economic point of view, power is to be derived from single phase AC supply. As discussed in Chapter - I

single phase bridge fully controlled line commutated converter is the most judicious choice for drive. Since speed reversal is desired 'non-circulating current' dual converter scheme is used as shown in Fig. 1. The armature supply is controlled while field current is kept constant. The fields of motor and generator are supplied by a single phase uncontrolled bridge rectifier.

2.2.1 Silicon controlled rectifiers rating :

The current to be controlled is 2.0 A, DC taking a safety factor of 2.5, the average continuous current of Thyristors to be used must be 5.0 A. The surge current rating of the SCR must be more than rotor block current with full voltage applied. In this case the peak short circuit current is 40 A. As usual to phase controlled circuits the SCR is to be derated for large firing angles. If the drive demands constant torque load characteristics the SCR continuous rating has to be properly increased.

SCRs are to be used in single phase bridge the peak inverse voltage across each SCR will be $\sqrt{2} * 230.0$ V. Assuming a safety factor of 3.0 the PIV rating of SCR must be 1000 V. The SCR available nearest to above rating is 2N1777, other ratings of interest for the said SCR are
(a) $I_g = 5.0$ mA, (b) $V_g = 2.5$ V, (c) $I^2t = 5.0$
(d) Turn on time = 5 μsec, (e) Maximum case temperature = 60°C

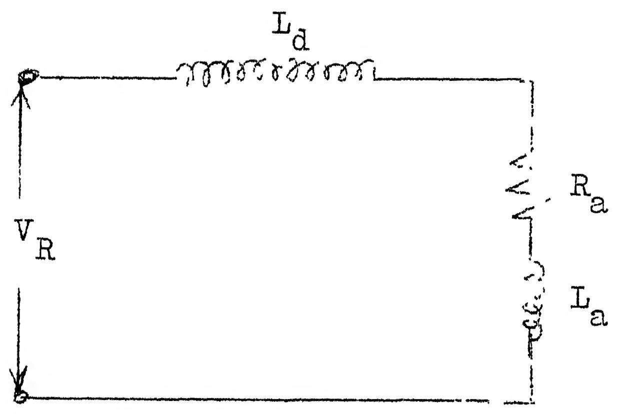
(f) PIV = 1200 V, (g) I_{dc} = 4.7 A, (h) I_{rms} = 7.8 A

A snubber circuit consisting of 24 ohm resistance and 0.1 μf capacitor is connected across each SCR of bridge to reduce $\frac{dv}{dt}$ effects.

2.2.2Calculation of Series Inductance Ld

In order to keep the current continuous in the armature of motor, so that it runs smoothly without any speed fluctuations, a series inductor L_d is used. Continuous armature current also reduces commutation problem and core losses. The value of L_d depends upon the armature current and resistance R_a. Since the armature current depends on the load, if the inductance is designed to keep the current continuous under lighter load it will be of very high value. This results in a large electrical time constant of motor, thereby producing slow response for the system. On the other hand if the series inductor is designed for full load conditions then there will be discontinuous armature current for light loads. Hence it is advisable to pick up that load condition which is going to be for most of the time. For this reason 75 percent load condition is considered.

$$I_a = 2.0 \times 0.75 = 1.5 \text{ A}$$



The above Fig. shows the circuit diagram of motor armature. Armature inductance (L_a) and resistance (R_a) are measured experimently. Maximum firing angle 'α' = 90° for rectifying mode under-continuous current condition.

Since the second harmonic is predominent in the armature voltage waveform it is assumed that all other harmonics have negligible effect.

Hence for current to be continuous, the peak value of second harmonic current should be less than average current (1.5 A).

For 230 V RMS supply, to calculate the second harmonic component first

$$v = \sqrt{2} \times 230 \cos \theta = 324 \cos \theta$$

Therefore, $b_n = \frac{2}{\pi} \int_0^{\pi} f(\theta) \sin 2n\,\theta \; d\theta$

where b_n is coefficients of sine terms.

Hence

$$b_2 = \frac{2}{\pi} \int_0^{\pi} 324 \text{ Cos } \theta \quad \sin 2\theta \; d\theta \qquad \text{For } \alpha = \pi/2$$

$$= 275.1 \text{ V peak}$$

Neglecting the armature resistance

$$2W(L_d+L_a) = \frac{275.1}{1.5} = 183.4 \text{ for second harmonic current to be just equal to load current (1.5 A)}$$

Hence

$$L_d = \left(\frac{183.4}{2.0 * 314}\right) -.055 \qquad \text{Heneries}$$

$$= 237 \text{ mH.}$$

Since this inductance is very large. To keep the system fast an inductance of 60 mH is connected which gives low electrical time constant of the motor. Hence the electrical time constant of the circuit is

$$\tau_e = \frac{L_d+L_a}{R_a} = \frac{115\text{x}10^{-3}}{5.6} = 20.5357 \text{ ms}$$

which is about one cycle of the input power frequency.

2.3.1 Control circuit design and description :

A brief design of the circuit is given. The design of the controllers is discussed is next chapter, as it requires a special treatment. The complete circuit is shown in Fig. 1.

2.3.2 Type of firing pulses :

To avoid the hunting in DC shunt motors it is necessary to gate the SCRs for a minimum of quarter cycle (5 ms). Because of this consideration if single pulse firing is used the pulse width has to be 5.0 ms. Transmission of such a large width pulse will require a bulky pulse transformer. Hence 20 μsec duration pulses are supplied to SCRs from the instant of desired firing angle 'α' to the end of half cycle. These 5 KHz pulses will reduce the size of transformer considerably and also produce reliable turn on of the SCRs.

2.3.3 The pulse amplifier :

As shown in Fig. 2 the pulse amplifier is used to amplify the pulse given out by logic circuit at the rate of 5 KHz and 3.0 V peak. Two transistors directly coupled are used for this purpose. This avoids the loading on logic gates and also keeps the last transistor off during non arrival of pulses. The pulse transformers are connected to form a collector load to power transistor and a 30 ohm resistor in emitter circuit is used to limit the current. The transistors are numbered T_{11} through T_6. Since the pulses are having very small fall and rise time, the switching of pulse transformer current is very sharp, which generates a unnecessary high voltages in primary as well as in secondary.

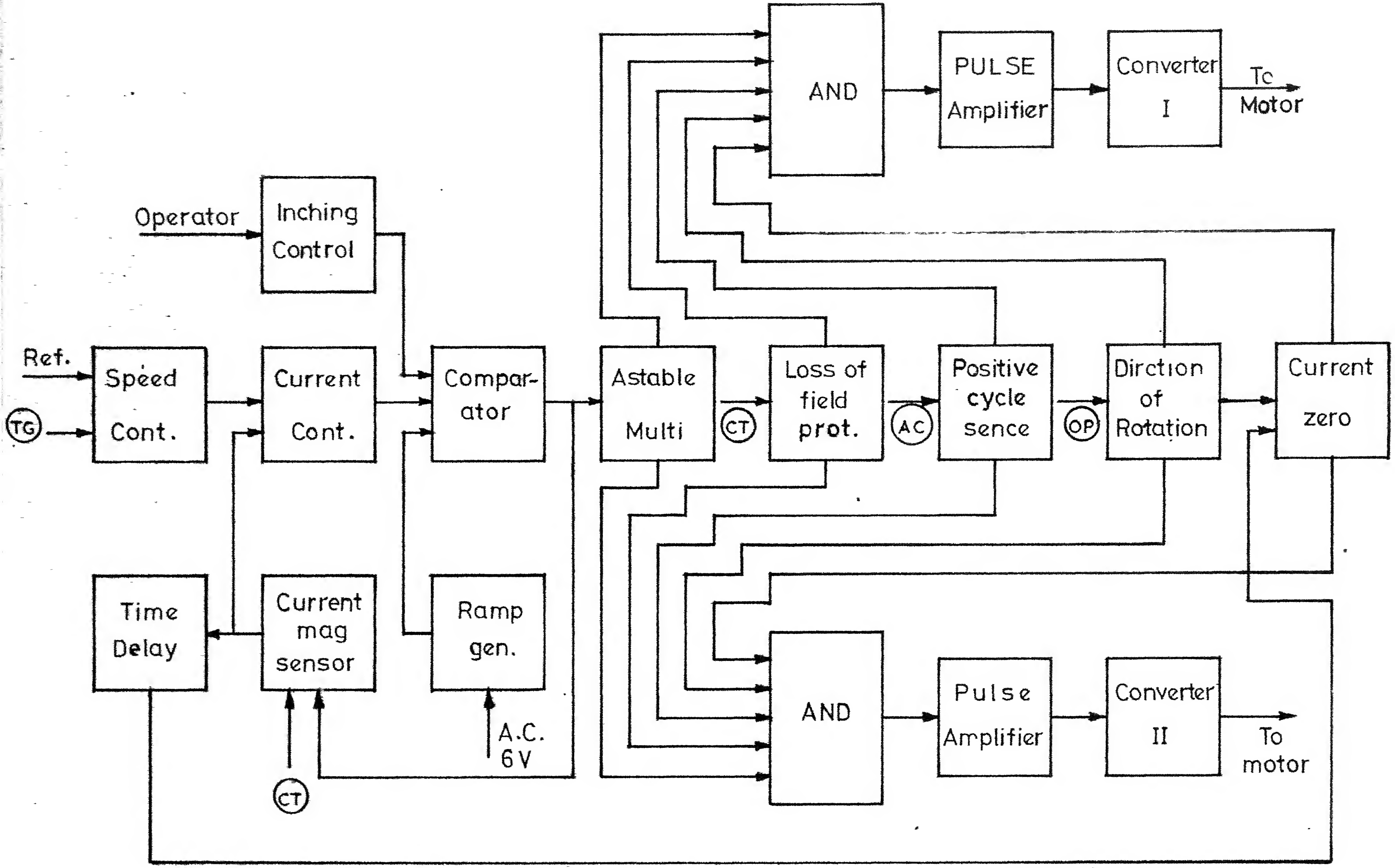


FIG.2 BLOCK DIAGRM OF CIRCUIT USED

This is determintal to transistors and also to SCR gates. To avoid these voltage spikes free wheeling diodes D_{32} through D_{29} along with the resistors and capacitors are used.

The pulse amplifier supplies the pulses at 10 V peak. Since the gate current required by SCRs is 7.0 mA, for reliable triggering a gate current of 15 mA is allowed at 2.5 V.

2.3.4 Pulse generator (Astable multi)

As discussed earlier, pulses at the frequency of 5 KHz are required from the instant of desired firing angle α to the end of half cycle of supply. For this purpose two NAND gate astable multi is used as it is very convenient to control its starting. It is shown in Fig. 1 by gates G12 and G13 whenever comparator (A_4) gives logical '0' the inverter G11 invert s it and the multi starts and as comparator goes to '1' it stops. Hence the time of firing is decided by the comparator.

2.3.5 Loss of field protection :

Here the field current is sensed by a series resistor on the AC side of the bridge of 5.6 ohms and an isolating transformer (Tr_7). This voltage is rectified and filtered and then given to logic circuit so that if it is '0' the firing pulses are not allowed to pass through and thus the main bridge stops conducting.

2.3.6 Selection of SCR to be gated :

In a converter since two thyristors are always reverse biased and the other two forward biased the firing pulses are to be steered to forward biased group only. For this purpose two transistors T_4 and T_5 are used. The bases of these transistors are supplied from the two halves of the secondary winding of transformer Tr_1, whose primary is connected to the supply voltage. In each half cycle one of the transistors conducts. Thus the output of these transistor provide the required information regarding the polarity of the supply wave. These outputs are fed to the logic gates and the proper SCR are selected.

2.3.7 Direction of rotation :

For this purpose two switches S_3 and S_4 are used. When turned on the switches give '1' to NAND gate. However, if both are switched by mistake, the exclussive OR gate circuit detects this condition and stops firing of both the bridges. Both of these switches also disconnect the reference to the speed controller when they are not switched on. The exclussive OR circuit is obtained by NAND gates G_4 through G_1. If either of the switch is on at a time the respective converter is ready.

2.3.8 Current zero :

This circuit is called for whenever the reversal is desired. This is shown by gate No. G_7 to G_{10}. The gate G_{10} and G_9 form a RS latch. The output of G_9 is fed back to G_7. Thus till G_9 gives zero (G_{10} will give '1') the circuit remains latched, and ignores the input to G_7 by G_{15} (Schimitt trigger for time delay) output of G_{15} goes to zero some time after. The armature current has become zero. Now as the position of S_3 and S_4 are reversed the exclusive OR gate becomes zero during the instant the both switches are in like position (either depressed or not). This zero from exclussive OR gate resets the RS latch and G_{10} now becomes zero thus stopping the firing pulses to all SCRs. As G_9 is '1' the G_7 output can be changed by the signal from G_{15}. By now the exclussive OR gate has become '1' because of proper desired position of switches (Reverse). Now as soon as time delay circuit (G_{15}) gives zero the RS latch again sets and G_9 becomes zero. Hence the G_{10} is 'one' and pulses can now pass through the gates. It again ignores any current zero henceforth till the exclussive OR gate output again becomes zero. (Because of the operation of switches S_3 and S_4).

2.3.9 Time delay circuit :

The purpose of this circuit is to delay the firing of converter SCRs after the current has become zero whenever reversal is desired. The current Transducer output is given to transistor T_1 which inverts and provides proper logic outputs to Schemitt trigger G_{15}. As the current becomes zero the transistor T_1 stops conduction therefore C_7 starts charging from 5 V supply through resistor R_{46} and R_{47} as soon as the C_7 charges to 1.6 V the Schemitt trigger changes the state to zero. Hence provides the time delay.

The Schemitt trigger is used to have a accurate threshold voltage of 1.6 V and no effect of slow voltage rise at capacitor C_7. R_{47} is provided to limit the capacitor discharge current through T_1, time delay of 20 ms is provided by this circuit.

2.3.10 Current Transducer :

In the scheme a resistance (R_{50}) in series with line and an isolating transformer Tr_2 are used to provide voltage proportional to current magnitude. This voltage is then rectified by bridge consisting of diodes D_{25} through D_{22}.

Since the current is not necessarily continuous in the circuit for all operating conditions, and also as the lowest

harmonic present in circuit is 100 Hz (2^{nd} harmonic) the filter required to smooth out these voltage pulses from the bridge, will have a large time constant, about 50 ms. This time delay is too large as the time constant of the controller discussed in next chapter, is only 28 ms. Hence a sample and hold circuit along with peak detector is used to provide the voltage proportional to the peak of the bridge voltage without any filter. The capacitor C_9 connected across diode bridge makes a simple peak detector. Across this capacitor JFET (F_2) is connected to discharge it at each half cycle of line current. This JFET (F_2) is made conducting for 0.5 ms by the pulse given out by transistor T_2 which is again driven by a monostable A_{11}. R_{49} a high value resistance is connected to by pass the bias current of amplifier A_{10}.

A high input impedance unity gain buffer is connected to C_9. The output of A_{10} is passed to C_8 through JFET (F_1) whenever it is made conducting by monostable A_{11}. This capacitor then holds the value and is buffered by A_9.

Operation sequence of the circuit proceeds as follows :

Whenever the comparator A_4 switches to zero (firing pulses are applied to converter) the transistor T_3 switches off and a sharp pulse by differentiating circuit C_{11} and R_{62} with R_{61} is given out which triggers monostable A_{11}. This mono

gives a positive pulse of 0.5 ms which turns on the JFET (F_1) and transistor T_2. Turning on the F_1 for 0.5 ms transfers the voltage output of A_{10} to holding capacitor C_8. This happens just after the firing of converter. Now as the mono flips back the T_2 turns off which produces a pulse through differentiating circuit C_{10}, R_{54} and R_{52}. R_{53}, R_{51} and diode D_{26} are used to reduce negative pulse magnitude when T_2 turns on to FET T_2. This pulse turns on the JFET F_2 which is after the C_8 has acquired the voltage held on by C_9. The F_2 turning on discharges the capacitor C_9 to nearly zero. This happens within one ms of firing of converter. C_9 is ready now to assume a new peak value of voltage given by bridge while C_8 holds the previous peak value and the sequence repeats. Thus the output is proportional to peak current delayed by one half cycle only.

2.3.11 Comparator :

To find the desired firing angle 'α' ramp comparator scheme is used. A ramp starting from the instant of zero crossing of AC supply voltage wave and going upto 9.5 ms (10 ms is the half cycle period for 50 Hz supply) is given to input of operational amplifier A_4 by resistance R_{27}. The hight of the ramp is adjusted to +7.0 V. An error signal from current controller (A_3) which is negative is

given through R_{26}. The resistances R_{26} and R_{27} are of equal value. Whenever positive going ramp is equal or greater than error signal the comparator output becomes zero. When error signal is greater (in magnitude) the comparator voltage remains + 4 V. The voltage levels are achieved by diodes D_9 and D_8. The D_9 does not allow the comparator voltage to go below -0.6 V while D_8 clips at + 4 V because of resistors R_{24} and R_{25}.

2.3.12 Ramp generator :

The ramp is generated by operational amplifiers A_8 through A_5. An A.C. voltage derived from line is given at inverting terminal of A_5 through resistor R_{29}. The output of this amplifier is clamped at $\pm$ 10 V by means of resistances R_{30}, R_{31}, R_{32}, R_{33} and diodes D_{10}, D_{11}, otherwise it is in open loop. Hence its gain is very high. As the A.C. voltage at input goes to positive or negative by small amount the output of A_5 becomes negative or positive respectively.

This action converts the sine wave into an inverted square wave. The square wave is then differentiated by C_4 and R_{34}. Which gives positive and negative pulses.

The negative pulses are applied to A_7 and positive to A_8 to start the ramp. Thus ramp starts as the supply wave crosses the zero. The hight of ramp is adjusted to +7.0 V by

R_{40} and R_{39} while the time is adjustable by P_2. The time is adjusted to be 9.5 ms.

2.3.13 Inching :

Switching S_1 the controller A_3 is disconnected from comparator and G_{14} (Schemitt trigger) is connected to comparator. The resistance R_{26} is connected to -V, this holds the comparator in non firing position. Now as soon as Pross button S_5 is pressed the capacitor C_{16} goes to ground. Thereby giving zero at input of G_{14}, so the G_{14} gives '1' at its output which is nearly 5 V. This voltage is applied through R_{28} to comparator and comparator issues the firing command. However, the capacitor gets charged through R_{71} and 5 V supply. As soon as its potential rises to 1.6 V the G_{14} comes back to zero and stops the firing pulses. The firing angle α is adjustable by resistance R_{28}.

2.3.14 Tacho feed back :

One more amplifier is shown in Fig. 1 that is A_1 which along with diodes D_2 and D_3 forms a inverter when ever tachogenerator gives positive output. Because motor has to run in both direction the tachowill reverse its polarity to keep the feed back negative at all time the amplifier A_1 is used.

2.3.15 Jogging operation :

Diode D_1 and resistor R_5 and R_6 are given to feed a negative signal of very low strength to speed controller. Hence this inhibits the firing of converter at zero reference setting due to noise pick up. Switches S_3 and S_4 (direction of rotation commond switches) are also used to apply the reference to speed controller when they are turned on. The jogging switches S_2 when pressed disconnects the reference pot P_1 and simultaneously connects a fixed bias to speed controller thus giving a slow rotation to machine.

CHAPTER III

DESIGN OF CONTROLLERS

3.1 Introduction

Since the controllers have major effect on the stability and performance of the system, they are to be designed from control system point of view. Two type of controller configuration namely proportional integral and proportional only are designed for speed feed back while proportional integral for current loop, are considered. To design the controllers, therefore, it is necessary to find out the transfer function of all blocks. The linearity is assumed for all blocks.

3.2.1 Calculation of transfer functions

The complete block diagram is shown in Fig. 3. The transfer functions for each block is indicated in the figure. The controller parameters are calculated on a P.U. basis.

3.2.2 Motor transfer function

The various parameters as shown in Fig. 3, are measured experimentally for motor. The field current is held constant. The measurement procedure is given in Appendix 'A'. From Appendix 'A' $T_e = 20.53$ msec $T_m = 109.8$ ms $B = 0.214$ and $K_w = 1.0$ normalized.

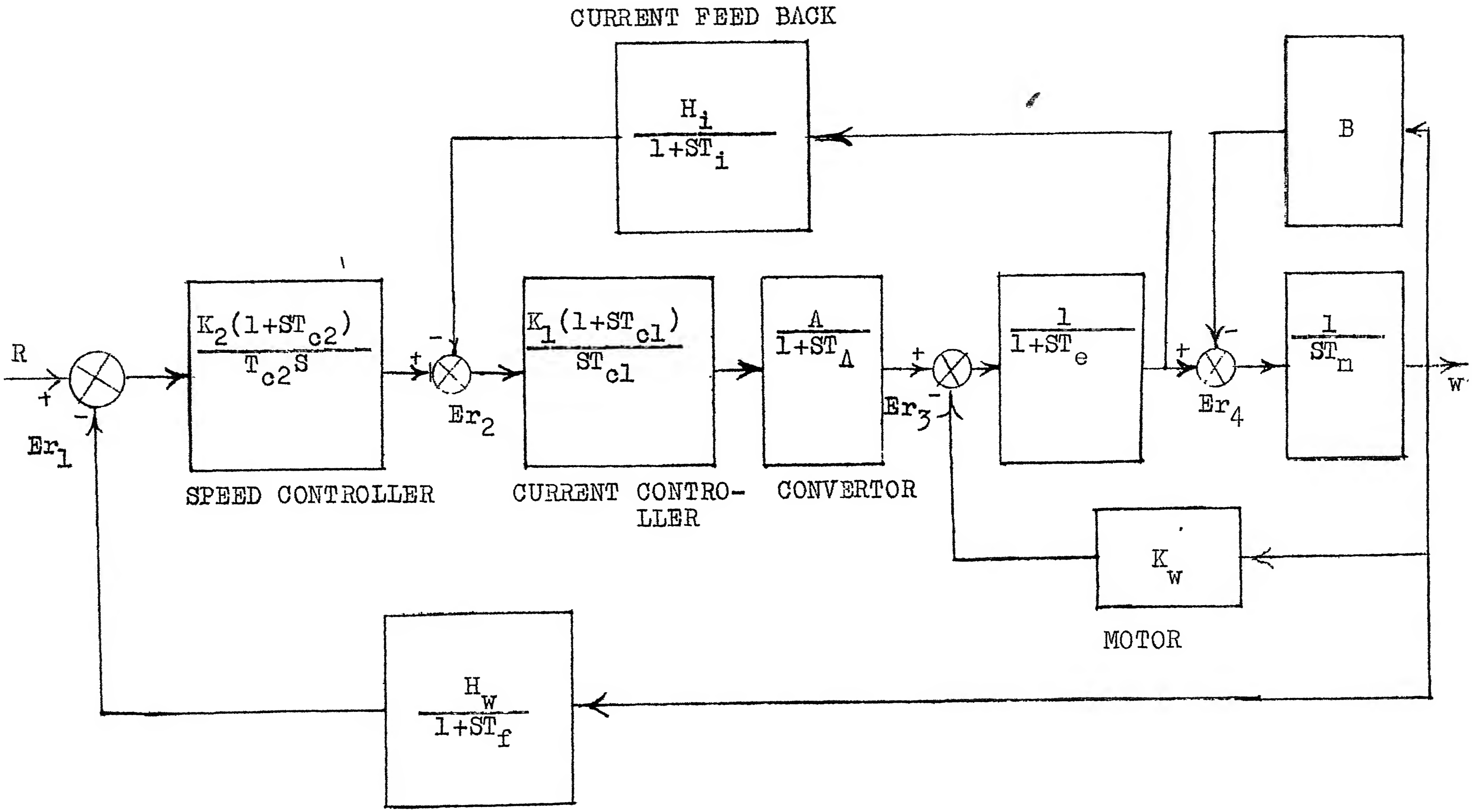


Fig. 3 CONTROL SYSTEM BLOCK DIAGRAM

The motor block is further simplified to suit the design as shown in Fig. 4.

where,

$$-\frac{1}{T_1} \text{ and } -\frac{1}{T_2} = \tfrac{1}{2}\left[-\left(\frac{B}{T_m}+\frac{1}{T_e}\right) \pm \left[\left(\frac{B}{T_m}+\frac{1}{T_e}\right)^2 - 4\left(\frac{B+1}{T_m T_e}\right)\right]^{\frac{1}{2}}\right]$$

on substituting all the constants

$$T_1 = 65.866 \quad \text{ms}$$

$$T_2 = 28.198 \quad \text{ms}$$

while $T_m/B = 513.0$ ms.

3.2.3 —— Base quantities

(i) The base speed is assumed to be 1500 RPM. This is the maximum rated speed of the motor.

Hence $w_o = \frac{1500 \times 2\pi}{60} = 157.0$ rad/sec. The base speed

(ii) The back emf constant K_b defined by the equation

$$\text{Back emf} \quad E_b = K_b w$$

is determined experimently and is found to be 1.4. Hence the base armature voltage is given by

$$V_R = K_b\, w_o = 1.4 * 157.0 = 220 \text{ V}$$

(iii) The starting current is taken to be base current when V_R is applied

$$I_{st} = \frac{V_R}{R_a} = \frac{220}{5.6} = 39.3 \text{ A}$$

where R_a is the armature resistance.

Hence the base torque

(iv) $M_{st} = K_b \, I_{st} = 1.4 \times 39.3 = 55.0$ Nw.m.

(v) The speed transducer used develops 1.0 Volt for 145 FPM of motor speed. Assuming zero steady state error reference voltage required to run the motor at base speed is

$$V_{cm} = \frac{1500}{145} = 10.34 \text{ V}$$

which is taken as base for control voltage.

(vi) Since the maximum firing angle be π (Ideally) it is assumed as base for firing angle.

3.2.4 Speed transducer :

Measured experimently the tachogenerator develops 1 Volt for 145 RPM of speed.

Hence the D.C. gain of tachogenerator becomes

$$H_w = \frac{1}{145/60} \quad \text{Volts/RPS}$$

Normalized to $\frac{1500}{145 * 10.34} = 1.0$ P.U.

Since a first order filter is used in series with techogenerator the complete transfer junction can be written as

$$\frac{H_w}{1+ST_f}$$ where T_f is the filter time constant.

3.2.5 Current transducer :

The current transducer used is shown in Fig. 1. It was measured experimently that it gives 3.8 V for 1.0 A of armature average current.

Normalizing it by base quantities

$$H_i = \frac{3.8/10.34}{1.0/39.3} = 14.44$$

As discussed in Chapter 2, Section 2.3.10, the transducer gives a delay of one half cycle (max) . We can neglect it for calculation as it is very small. The complete transfer function of current transducer will be

$$\frac{H_i}{1+ST_i}$$ where $T_i = 5 \times 10^{-3}$ sec. (average)

3.2.6 Converter

Since the single phase bridge is used the average voltage E_{dc} for this bridge is given by

$$E_{dc} = 0.9\ V_{rms} \cos \alpha$$

Therefore, $$\frac{d\ E_{dc}}{d\alpha} = -0.9\ V_{rms} \sin \alpha$$

normalizing it

$$\frac{d\ (E_{dc}/V_R)}{d(\alpha/\pi)} = -0.9\ \frac{V_{rms}}{220}\ \pi \sin \alpha\ .$$

For E_{dc} of 220 V the required V_{rms} at $\alpha = 30^\circ$ (assumed operating point) is given by

$$220 = 0.9\ V_{rms} \cos 30^\circ$$

Therefore, $$V_{rms} = \frac{220}{0.9 * 0.866}$$

Hence,

$$\frac{d\ (E_{dc}/V_R)}{d(\alpha/\pi)} = -\ \frac{0.9 * 220 \times \pi}{0.9 * 0.866 \times 220} \sin \alpha$$

$$= -1.154\ \pi \sin \alpha$$

For $\alpha = \pi/2$ the maximum value of expression is

$$-1.154\ \pi$$

and for $\alpha = \pi/6$

$$\frac{d\ (E_{dc}/V_R)}{d(\alpha/\pi)} = -1.154 * 0.5$$

Hence the average [1]

$$\frac{d\ (E_{dc}/V_R)}{d(\alpha/\pi)} = -2.72$$

Now as the error voltage from current controller applied to comparator varies from 0 to -7.0 V the firing angle varies from 0 to π (Because of ramp characteristics).

Hence the comparator transfer function

$$= \frac{\alpha}{V_e} = \frac{\pi}{-7.0}$$

Normalizing it $\frac{\alpha/\pi}{v_e/V_{cm}} = -\frac{10.34}{7.0} = -1.4771$

Hence the gain of Thyristor amplifier (converter and comparator together) is given by

$$(-2.72) \cancel{+}\!\times (-1.471) = 4.01$$

As the firing angle α is adjusted after every half cycle. The average delay is assumed to be [1] 5 ms. Hence the transfer function of converter

$$\frac{E_{dc}(s)}{V_e(s)} = \frac{4.01}{1+0.005\ s}$$

3.3.1 Design of current controller :

The current feed back is used due to following reasons :

(i) Because the electrical time constant of the motor is much smaller than mechanical time constant whenever there is supply voltage fluctuations the armature current falls almost immediately than speed. The current controller being faster than speed controller will correct the supply fluctuations without any appreciable difference is motor speed.

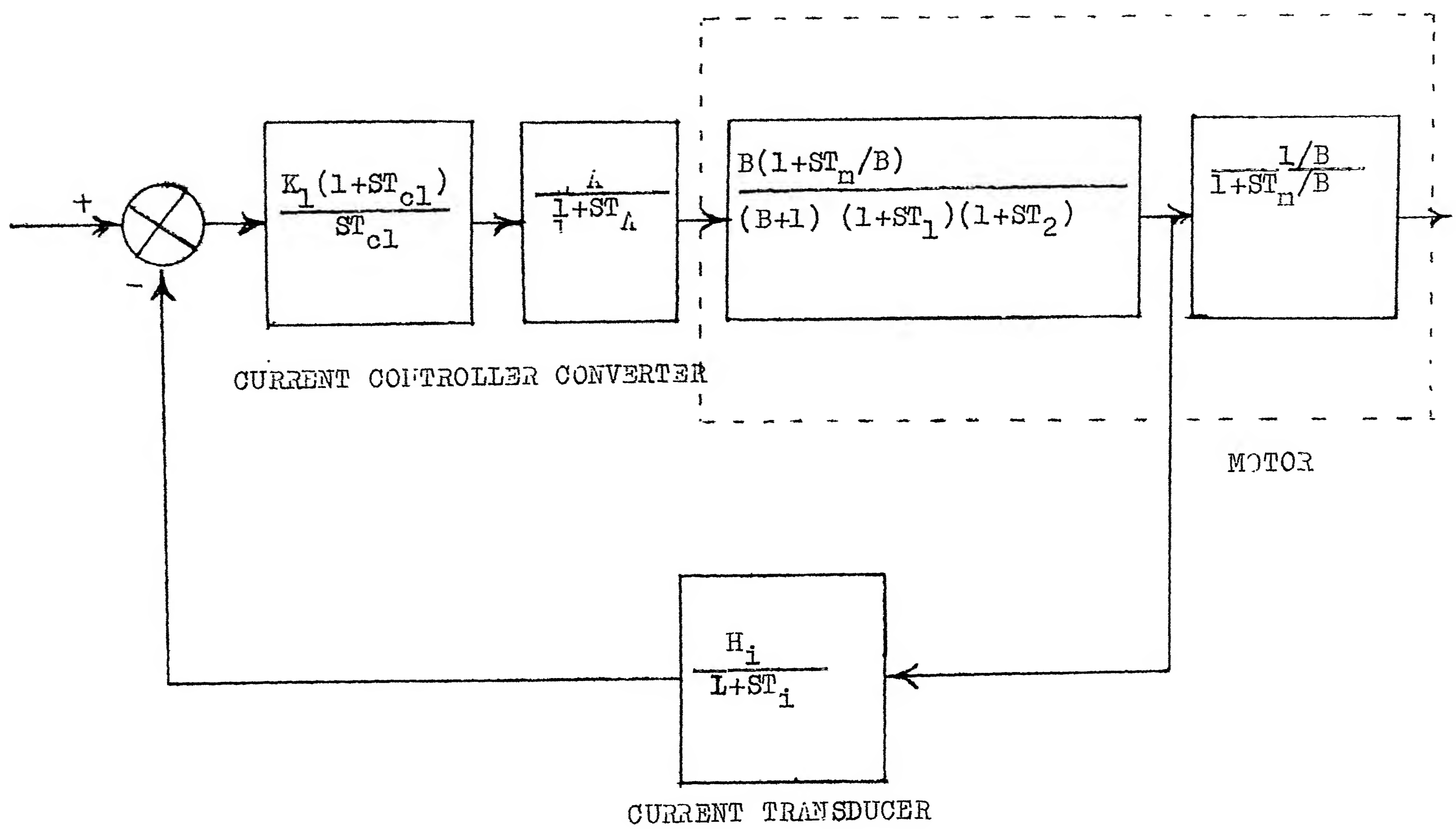


Fig. 4 BLOCK DIAGRAM FOR THE DESIGN OF CURRENT CONTROLLER

(ii) By making the current control as over riding command on speed controller (As shown in Fig. 3) and clipping the reference to current controller (output of speed controller) the maximum current through converter and hence through the motor can be controlled very easily, which avoids the overloads and also provides for acceleration control for the motor.

The current controller is chosen to be proportional integral controller (PI) as it gives zero steady state error (For step input) and also it will reduce the firing angle α from π slowly. Thereby giving a smooth start.

The PI controller has got the transfer function as follows :

$$\frac{K_1 (1 + S T_{c1})}{S T_{c1}}$$

where K_1 is the gain constant and T_{c1} is time constant of controller. The detailed circuit diagram is given in Fig. 1 as amplifier A_3. The time constant is given by $C_3 * R_{20}$ while gain constant $K_1 = \frac{R_{19}}{R_{20}}$.

In Fig. 4 the current loop is shown alongwith motor. The open loop transfer function of the loop can be written as

$$GH_i(s) = \frac{K_1(1+ST_{c1})}{S T_{c1}} * \frac{A}{1+ST_A} * \left(\frac{B}{B+1}\right) \frac{(1+ST_m/B)}{(1+ST_1)(1+ST_2)} * \frac{H_i}{1+ST_i}$$

As T_i is very small 5 ms . pole associated with

it can be neglected. Since the time constant T_m/B is very large (513 ms) compared to the time constants T_1 (65 ms) T_2 (28.2 ms) and T_A(5 ms). The loop gain function in the vincinity of gain cross over frequency can be approximated to

$$GH_i(s) = K' \frac{(1+s\,T_{cl})}{(1+sT_1)\,(1+sT_2)\,(1+sT_A)}$$

where

$$K' = \frac{K_1\ A\ H_i\ T_m}{T_{cl}(B+1)}$$

It is desirable to arrive at a second order system by choosing T_{cl} such that it cancels one of the plant poles. The resulting second order system should have a damping factor of 0.707 and a gain K' as large as possible. Since accuracy increases with K', $T_A < T_2 < T_t$.

Therefore the open loop gain is

$$GH_i(s) = \frac{K'}{(1+sT_1)\,(1+sT_A)}$$

Hence the characteristic equation is

$$1+GH_i(s) = 1 + \frac{K'}{(1+sT_1)\,(1+sT_A)} = 0$$

or $(T_1\ T_A)\ s^2 + s\ (T_1 + T_A) + K' + 1 = 0$

or $s^2 + s\ \dfrac{T_1 + T_A}{T_1\ T_A} + \dfrac{K' + 1}{T_1\ T_A} = 0$

assuming $K' \gg 1$ (as will be shown)

$$\varepsilon = 0.707 = \frac{1}{2}\frac{(T_1 + T_A)}{T_1\ T_A} \times \frac{\sqrt{T_1\ T_A}}{\sqrt{K'}}$$

$$\sqrt{2} = \frac{T_1 + T_A}{\sqrt{K'(T_1\ T_A)}}$$

Since $T_1 \gg T_A$ neglecting T_A from numerator

$$K' = \frac{1}{2}\ \frac{T_1}{T_A}$$

Hence

$$K_1 = \frac{1}{2}\left(\frac{T_1}{T_A}\right)\left(\frac{T_{c1}(B+1)}{T_m AH_i}\right)$$

Substituting the value of parameters

$$K_1 = \frac{1}{2}\left(\frac{65.866}{5.0}\right)\left[\frac{28.2}{109.8} * \frac{1.214}{4.01 * 14.44}\right] = 0.035466$$

and $T_{c1} = 28.2$ ms

Assuming the value of capacitor C_3 as 0.47 µf.

$$R_{20} = \frac{28.2}{0.47}\ K = 60\ K$$

Since $K_1 = \dfrac{R_{19}}{R_{20}}$

Hence $\quad R_{19} = 0.035 * 60 = 2.1\ K \quad 2.2\ K$

Since the maximum current is to be limited to 2.0 A (average)

maximum voltage output from speed controller is 7.0 V

Hence $\dfrac{7.0/V_{cm}}{R_{22}} = \dfrac{(2/39.3) * H_i}{R_{20}}$

$R_{22} = 56\ K.$

Therefore the controller transfer function is

$$\frac{0.035\ (1+0.0282\ S)}{0.0282\ S}$$

and the components are as follows

$C_3 = 0.47\ \mu F$

$R_{20} = 60\ K$

$R_{22} = 56\ K$

$R_{19} = 2.2\ K$

3.3.2 Design of speed controller

Two types of controller configurations are used :

(i) The PI controller which gives zero steady state error.

(ii) The proportional controller which gives a faster response but produces regulation in speed. The design of both the configurations are discussed below. and performance characteristics are given in next chapter.

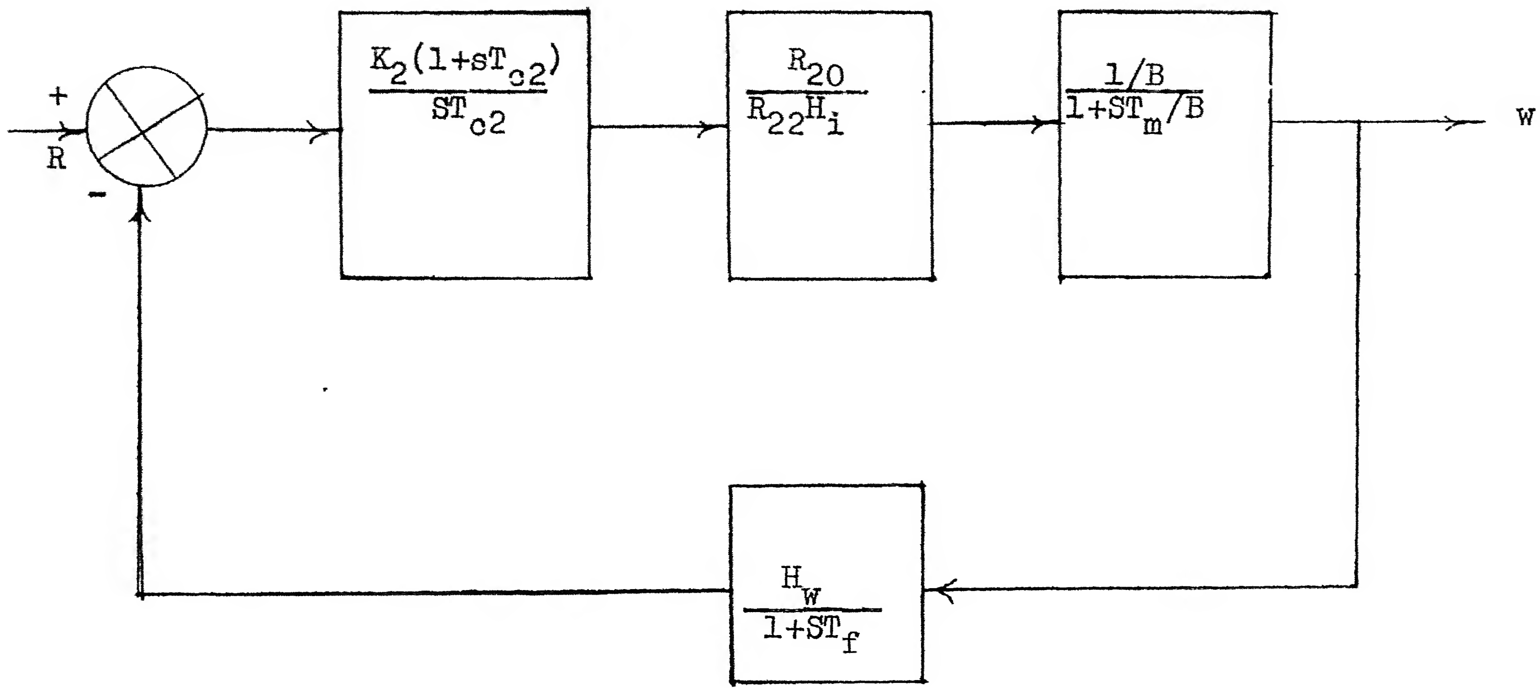


Fig. 5 : SYSTEM BLOCK DIAGRAM FOR THE DESIGN OF SPEED CONTROLLER

3.3.2.1 PI controller for speed :

For designing this controller it is necessary to approximate the current loop by a low order system. It is shown in Section 3.2.1 that the current loop is actually a fourth order system and it has been approximated by a second order system for design purpose. As discussed in previous section the gain of the current loop is made large. Hence we can write

$$\frac{G_i}{1+GH_i} = \frac{G_i}{GH_i} = \frac{1}{H_i}$$

Since there is difference in R_{20} and R_{22} the complete transfer function for current loop is approximated to

$$\frac{R_{20}}{R_{22}H_i} \text{ only.}$$

Hence the open loop transfer function of speed loop Fig. 5. is given by

$$GH_w = \frac{K_2(1+sT_{c2})}{sT_{c2}} * \frac{R_{20}}{R_{22}H_i} * \frac{1/B}{1+sT_m/B} * \frac{H_w}{1+sT_f}$$

Based on the numerical values of the time constants involved here the following approximation can be made in the vicinity of gain cross over frequency w_c.

(i) The term $\frac{1}{1+sT_m/B}$ can be taken as $\frac{1}{sT_m/B}$

With this approximation the loop gain function of the speed loop can be simplified as

$$GH_w(s) = \frac{K_2 R_{20} H_w}{T_{c2} R_{22} H_i T_m} \quad \frac{(1+sT_{c2}}{s^2(1+sT_f)}$$

$$= \frac{K_2(1+T_{c2}s)}{sT_{c2}} * \frac{1}{T_L \; s(1+sT_f)}$$

where $T_L = \frac{R_{22} H_i T_m}{R_{20} \; H_w}$

on substitution $T_L = 1.48$ s

Hence the numerator of

$$1+GH_w = s \; T_{c2} \; T_L \; s^2(1+sT_f) + K_2(1+T_{c2}s)$$

From stability considerations $T_{c2} > T_f$

The other two parameters T_{c2} and T_f are so chosen that the the $1+GH_w$ equation has one real root and other two are complex conjugate with a damping factor of 0.707

Assuming $T_f = 220$ ms and $K_2 = 0.4.,$

the $T_{c2} = 6.9$ sec.

Hence the controller transfer function is given by

$$\frac{0.4(1+6.9\ s)}{6.9\ s}$$

and that of speed transducer as $\frac{1}{1+.22\ s}$

This transfer function is realized by the amplifier block A_2 in Fig. 1. The output of speed controller is clamped to +0.6 to -7.0 V by diodes D_5 and D_4 along with the resistor R_{13}, R_{14} and Pot P_3. The Pot P_3 gives the variation in negative clamp level thereby varying the maximum current to armature and thereby controlling the acceleration.

Assuming C_2 = 12.5 μf

as T_{c2} = 6.9 sec.

R_{12} = 6.9

Hence R_{12} 560 K

As the H_w = 1.0

R_{11} = 560 K

$K_2 = 0.4 = \frac{R_{15}}{R_{12}}$

Hence R_{15} 220 K.

Therefore, the controller transfer function is

$$\frac{0.4(1+7.0\ s)}{7.0\ s}$$

and components are :

$C_2 = 12.5\ \mu f$

$R_{12} = 560\ K$

$R_{11} = 560\ K$

$R_{15} = 220\ K$

3.3.2.2 Proportional controller :

Let K_3 be the gain (Transfer function also) of controller. Since T_A (5 ms) and T_i (5 ms) are very small they are neglected. Referring to Fig. 4. the current loop gransfer function can be calculated as follows :

$$GH_i(s) = \frac{K_1(1+sT_{c1})}{sT_{c1}} \quad A * \frac{B}{B+1} \quad \frac{1+sT_m/B}{(1+sT_1)(1+sT_2)} * H_i$$

$$\text{and } G = \frac{K_1(1+sT_{c1})}{sT_{c1}} * A * \frac{B}{B+1} \quad \frac{1+sT_m/B}{(1+sT_1)(1+sT_2)}$$

since $T_{c1} = T_2$

$$G_i(s) = \frac{G(s)}{1+GH_i(s)} = \frac{K_1 *A*B* (1+sT_m/B)}{(B+1)\ T_{c1}\ s(1+sT_1) + K_1 *A*B*H_i\ (1+sT_m/B}$$

which is the equivalent transfer function of the current loop.

Hence the loop transfer function for speed loop assuming proportional controller with transfer junction K_3 in place of PI controller in Fig. 3.

$$GH_w(s) = \frac{H_w\ K_3\ K_1\ A\ B\ (1+sT_m/B)}{[(B+1)\ T_{c1}\ s(1+sT_1) + K\ A\ B\ H_i\ (1+sT_m/B)]\ (1+sT_f)}$$

After substituting the numerical values except K_3 which is assumed to be unity GH_w is plotted on GH plane, giving Nyquist plot for the system with $K_3 = 1.0$.

From Nyquist plot of above transfer function the $K_3 = 40$ for proper gain and phase margins.

The R_{12} input resistance of the controller is taken to be 47 K and R_{15} (feed back resistance)works out to be :

$$R_{15} = 40 * 47 = 1.78\ M$$

The capacitor C_2 is removed.

The performance of the above closed loop system was tested with and without current feed back and the performance is given in next chapter.

CHAPTER IV

PERFORMANCE

4.1 Introduction

The performance of the control system discussed in the last two chapters is obtained under the following conditions :

(i) PI controller for speed loop with current feed back

(ii) PI controller for speed loop without current feed back

(iii) Proportional controller for speed loop with current feed back

(iv) Proportional controller for speed loop without current feed back

(v) Open loop control, without any feed back signal

With all the above five variations the steady state performance (speed torque characteristics) and dynamic performance (step switching the load) without any initial load and with some initial load, was observed. The dynamic performance of the system with PI controller with and without current feed back is also obtained for step change in supply voltage. A frictional load, is used for above studies. However, the dynamic performance of PI speed controller with current feed back is also calculated numerically on the digital computer for constant torque load.

4.2.1 Steady state performance of the system

Torque speed characteristics are found experimently under various schemes as given in Section 4.1. The torque was calculated by measuring the power input to motor and subtracting the armature losses.

4.2.2 PI controller for speed loop with current feed back

The scheme is same exactly as shown in Fig. 3. The frictional load is used for the experiment. The readings are given in Table 1 and curves are shown in Fig. 6 for various speed settings. Speed is given in RPM and Torque IN Nw.m.

TABLE 1

Torque speed characteristics for PI controller with current feed back

Speed setting 290 RPM		Speed setting 435		Speed setting 580		Speed setting 725		Speed setting 1160	
Torque	Speed	Torque	Speed	Torque	Speed	Torque	speed	Torque	speed
0.438	290	0.4	435	0.4	580	0.42	725	0.578	1160
0.497	290	0.454	435	0.445	580	0.5	725	0.719	1160
0.5438	290	0.5	435	0.48	580	0.576	725	0.89	1160
0.612	290	0.56	435	0.57	580	0.66	725	0.94	1160
0.724	290	0.77	435	0.6	580	0.71	725	1.07	1160
0.83	290	0.87	435	0.688	580	0.766	725	1.155	1160
1.02	290	1.06	435	0.788	580	1.05	725	1.4	1160

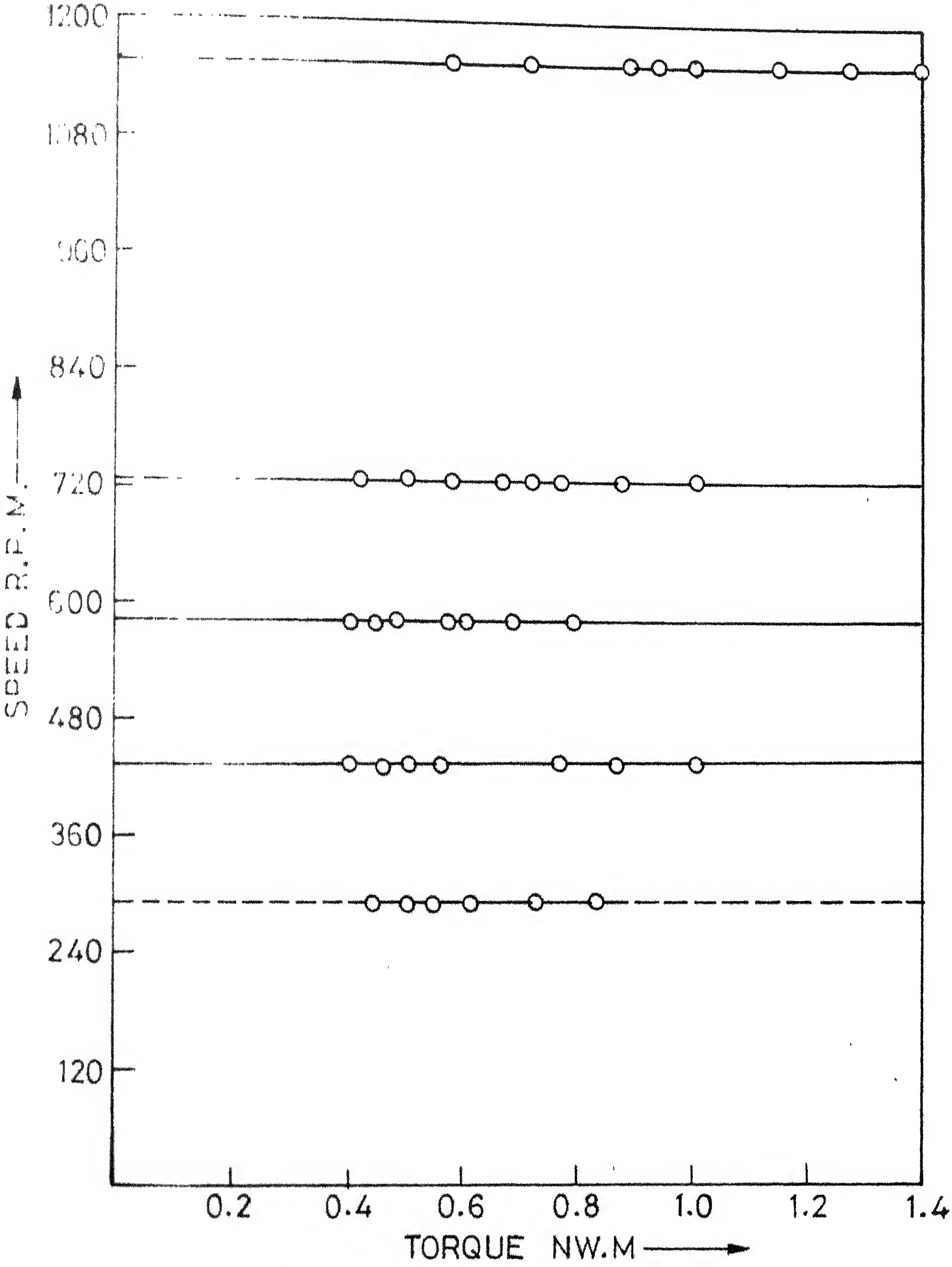


FIG.6 P.I. CONTROLLER WITH CURRENT FEED BACK

4.2.3 PI controller for speed without current feed back

Here the torque speed characteristics are found out without current feed back, The results are given in Table 2 and curves are shown in Fig. 7 for various speed settings.

TABLE 2

Speed torque characteristics for PI controller without current feed back

Torque in Nw.m and speed in RPM

Speed setting 290		Speed setting 435		Speed setting 507		Speed setting 580		Speed setting 725	
Torque	Speed	Torque	Speed	Torque	Speed	Torque	Speed	Torque	Speed
0.44	290	0.4	435	0.471	507	0.446	580	0.45	725
0.5	290	0.454	435	0.55	507	0.49	580	0.5	725
0.543	290	0.5	435	0.61	507	0.55	580	0.61	725
0.61	290	0.56	435	0.67	507	0.6	580	0.71	725
0.72	290	0.61	435	0.73	507	0.68	580	0.88	725
0.85	290	0.918	435	0.84	507	0.76	580	1.06	725
		1.06	435	0.95	507	0.86	580		
				1.17	507	1.06	580		

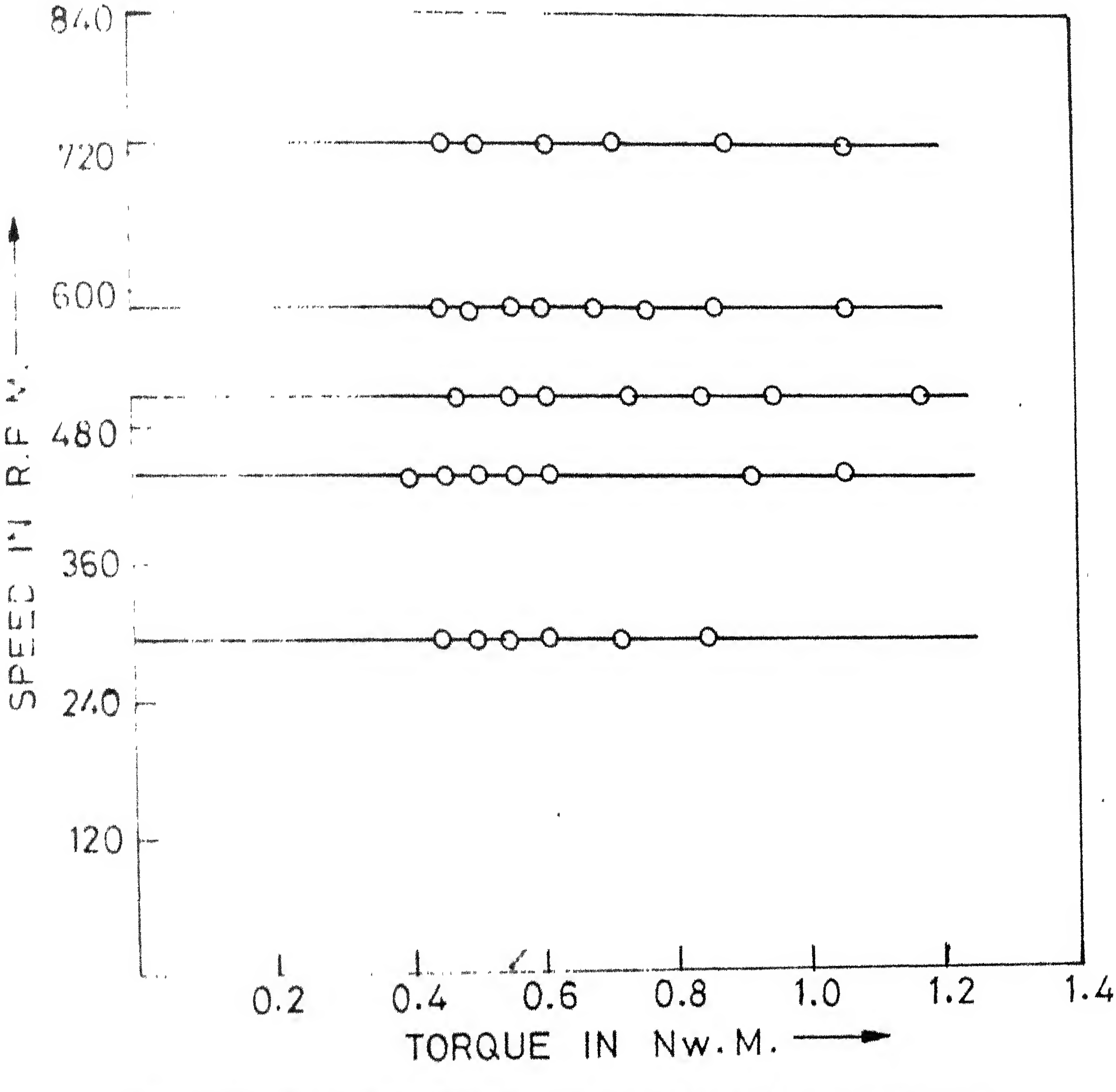


FIG. 7 P.I. CONTROLLER WITHOUT CURRENT FEED BACK

4.2.4 Proportional controller with current feed back

The design of proportional controller is discussed in Chapter 3 Section 3.3.2.2. The steady state performance (Torque speed characteristics) are given in Table 3 and curves are shown in Fig. 8.

Table 3

Torque speed characteristics of proportional controller with current feed back

Torque in Nw.m speed in RPM

Set speed 435		Set speed 522		Set speed 638		Set speed 725		Set speed 1015	
Torque	Speed	Torque	Speed	Torque	Speed	Torque	Speed	Torque	Speed
.55	435	.598	522	.58	638	.57	725	.66	1015
.79	423.4	.82	521	0.86	633	.8	721.0	.95	1008
.885	414.7	1.09	520	1.08	626	1.0	717.75	1.07	996
0.997	406.	1.24	519.1	1.23	623.5	1.15	710	1.17	991
1.15	395.8	1.38	517.65	1.38	622	1.3	703	1.28	986

4.2.5 Proportional controller without current feed back

The current feed back is removed and performance is studied the results are given in Table 4 and curves are shown in Fig. 9.

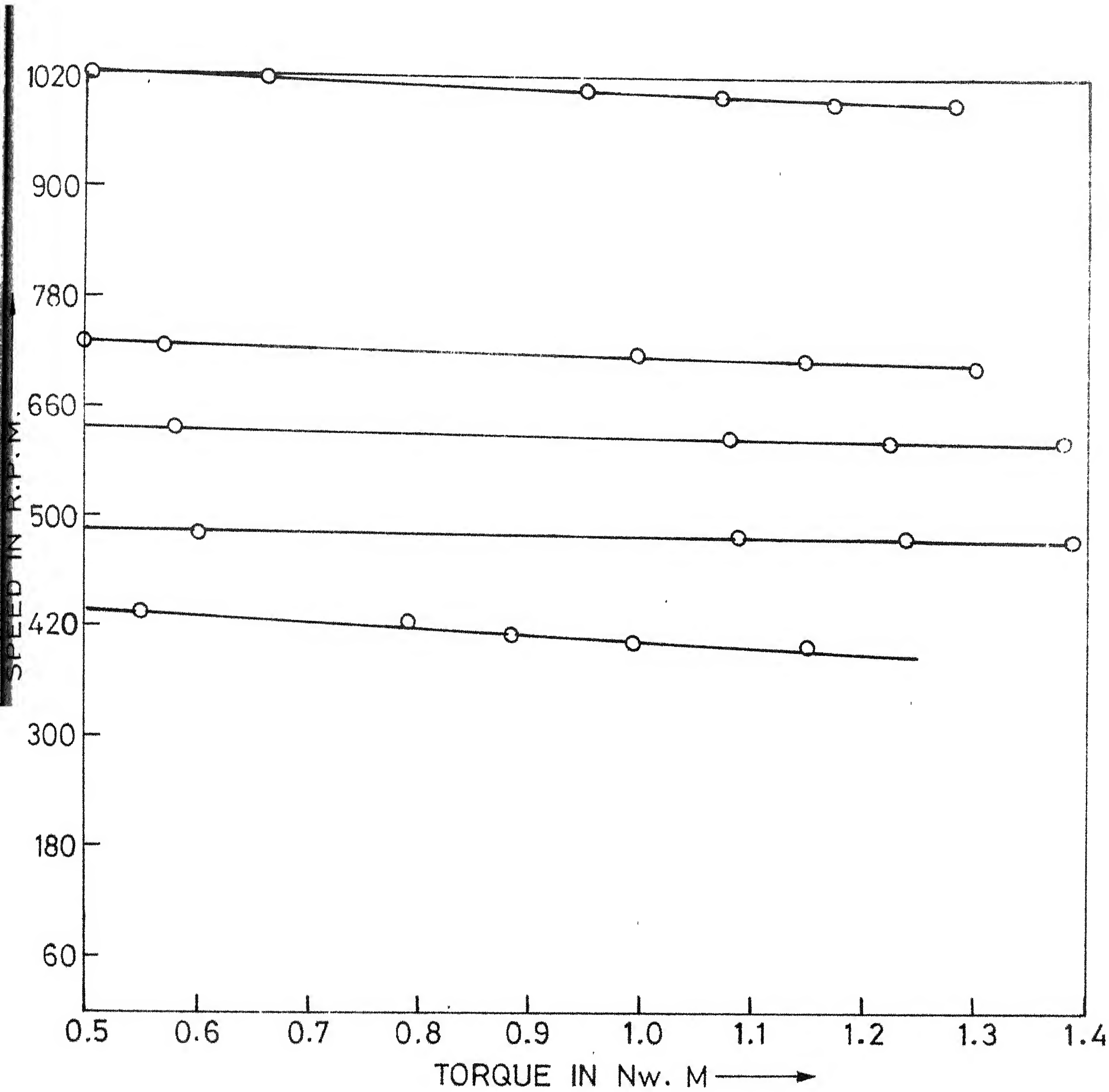


FIG. 8 PROPORTIONAL CONTROLLER WITH CURRENT FEED BACK

Table 4

Torque speed characteristics with proportional controller without current feed back

Torque IN Nw m Speed in RPM

Set speed 290		Set speed 435		Set speed		Set speed 580		Set speed 725	
Torque	Speed	Torque	Speed	Torque	Speed	Torque	Speed	Torque	Speed
.39	290	.42	435	.57	478.5	.56	580	0.60	725
.5	282.75	.58	420.5	1.04	464	0.63	560	0.676	720
.608	275.5	.75	413.25	.676	468	.72	570	0.76	713.8
.675	268.25	.86	406	.801	460	.875	563.8	0.94	700
.9	240.8	.975	390	.875	454	1.06	558	1.04	694
1.105	225	1.076	380	1.01	442	1.18	554	1.15	696

4.2.6 Open loop control

The speed and current feed backs are removed. The firing angle is set at a point without any external load. Then the load is varied and results are listed in Table 5 while curves are shown in Fig. 10.

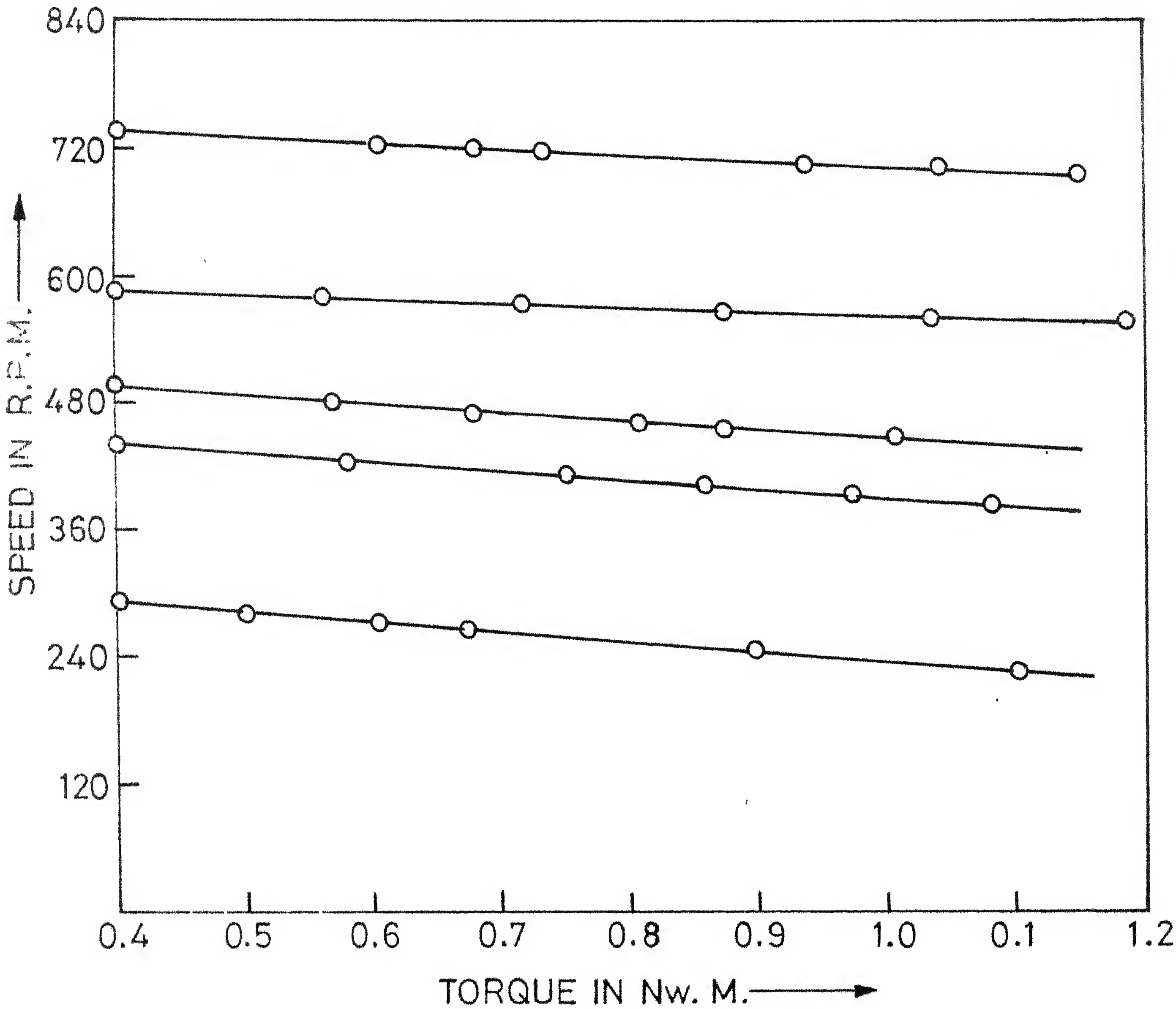


FIG. 9 PROPORTIONAL CONTROLLER WITHOUT CURRENT FEED BACK

Table 5

Torque speed characteristics with open loop control

Torque IN Nw. m speed in RPM

Set speed 290		Set speed 435		Set speed 580		Set speed 725		Set speed 870	
Torque	Speed	Torquee	Speed	Torque	Speed	Torque	Speed	Torque	Speed
.496	290	.535	435	.578	580	.6	725	.684	870
.568	253.75	.62	398.75	.673	507.5	.73	623.5	.803	797.5
.64	217	.7	319	.75	464	.844	565.5	.953	725
.643	210	.726	297.25	.835	420.5	1.027	478.5	1.107	652.5
.66	195.75	.84	217.5	.92	377	1.138	435	1.197	609
.721	166.75	.91	151	1.03	319	1.34	348	1.373	551
								1.65	464

4.3 Dynamic performance

The dynamic performance of the system is observed with step change in load (a) when the motor was on no load, (b) with the initial load of 0.5 A a frictional load of 0.1 A is switched on suddenlly and the speed is observed. The time speed curve is recorded on a recorder. This experiment is carried out with all the schemes mentioned in Sec. 4.1.

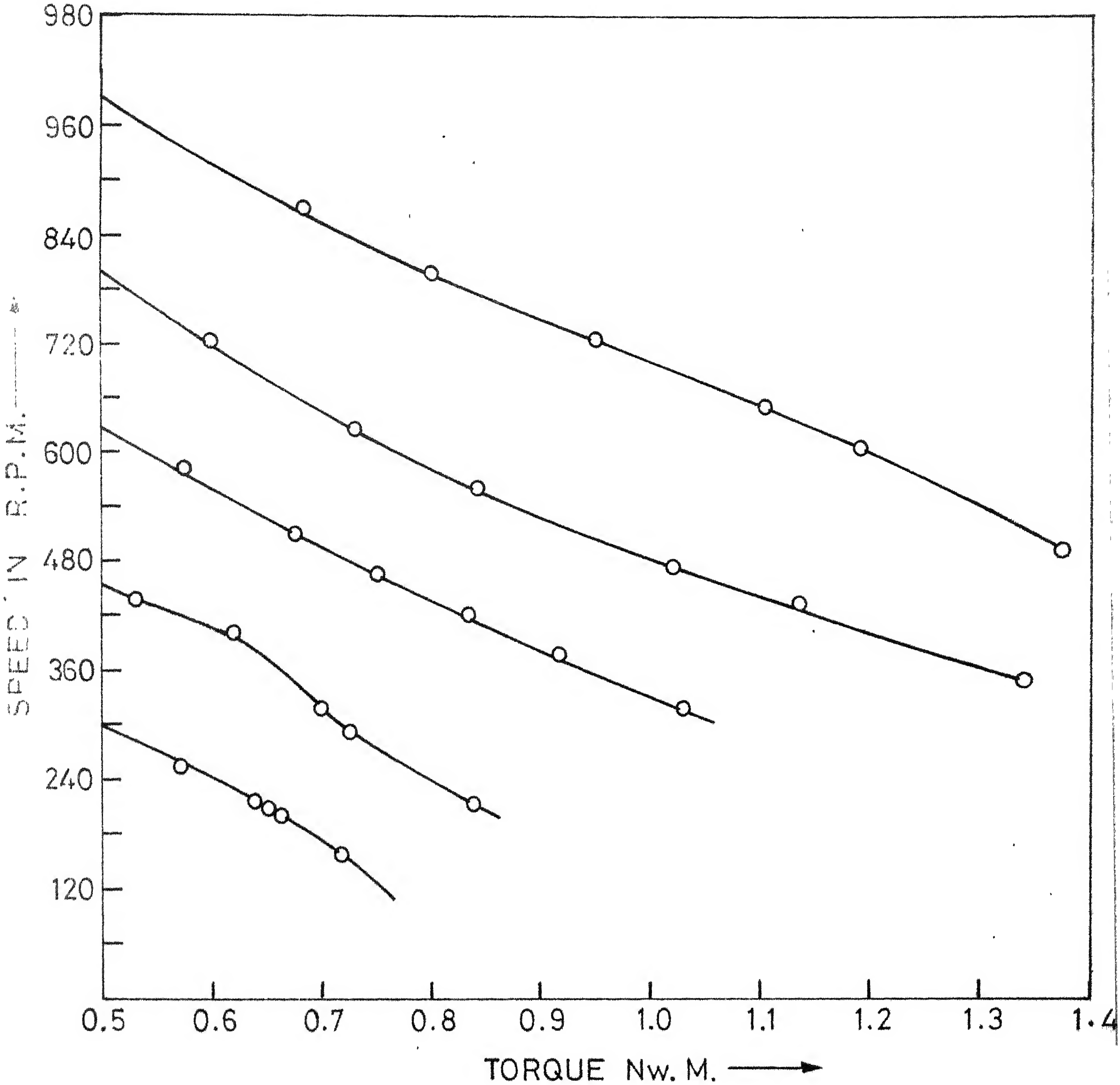


FIG.10 OPEN LOOP CONTROL

4.3.1 PI controller with current feed back

The scheme is set as discussed earlier, a frictional load of 0.1 A is switched on suddenlly and speed change is observed with and without initial load the results are given in table 6 and curves in Fig. 11.

Table 6

Time speed characteristics of PI controller with current feed back

Time in seconds speed in RPM

Without initial load		With initial load	
Time	Speed	Time	Speed
0.0	870	0	870
0.5	810	1.0	850
1.0	790	2.0	840
1.5	770	2.0	840
2.0	750	3.0	830
3.0	730	4.0	830
4.0	730	6.0	850
6.0	750	10.0	860
8.0	770		
10.0	810	14.5	870
13	850		
16	865		
18	870		

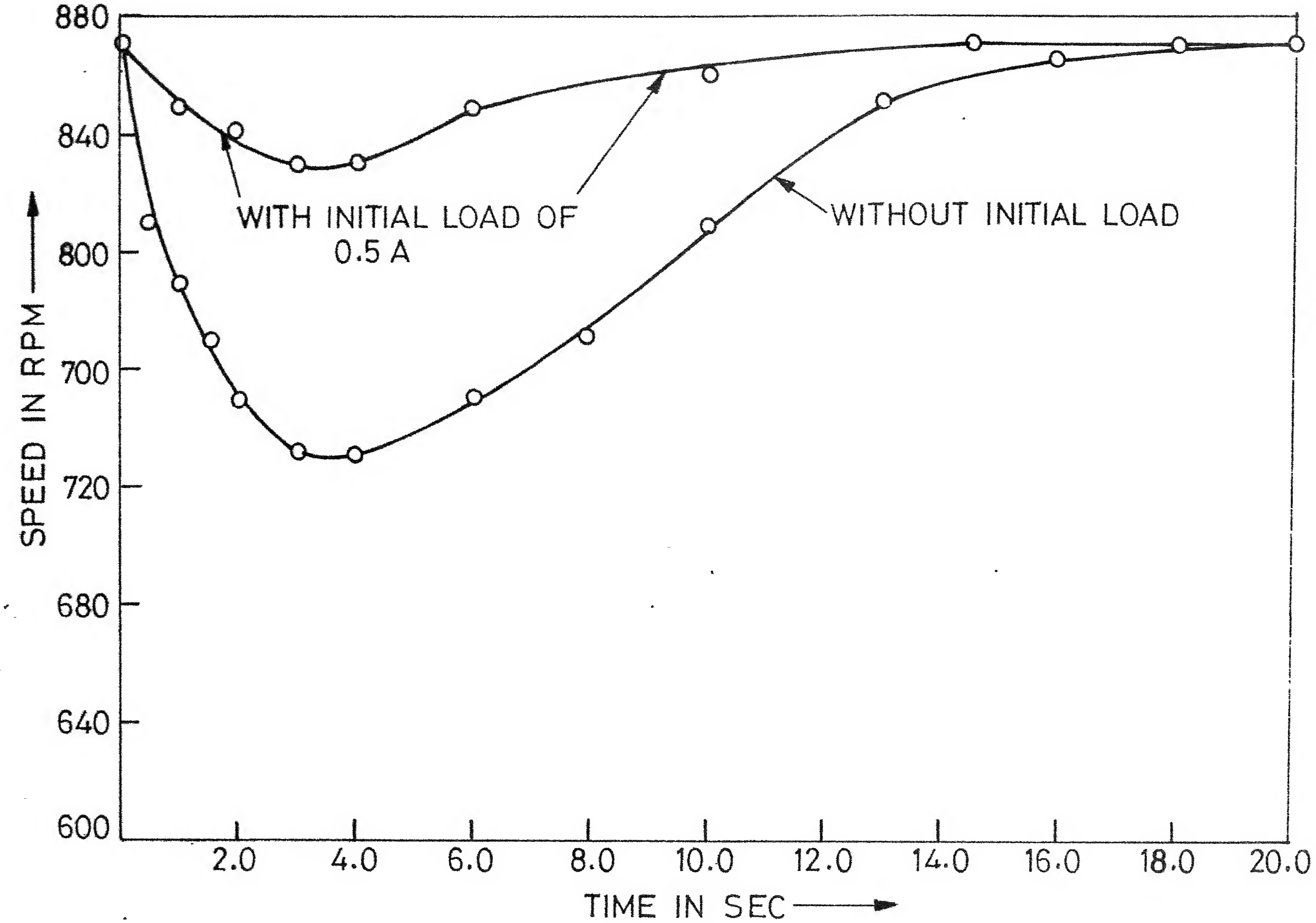


FIG.11 P.I.CONTROLLER WITH CURRENT FEED BACK STEP FRICTIONAL LOAD

4.3.2 PI controller without current feed back

The current feed back is removed and then the experiment was repeated. The results are given in Table 7 and curves are shown in Fig. 12.

Table 7

Speed time curve with PI controller without current feed back

Time in seconds - Speed in RPM

Without initial load		With initial load	
Time	Speed	Time	Speed
0	870	0	870
0.12	850	.5	850
0.25	830	1.0	840
0.37	810	1.5	835
0.62	787.14	2.0	840
1.12	745.7	7.5	850
1.62	745.7	22.0	870
5.62	787.14		
11.12	828.5		
22.12	870		

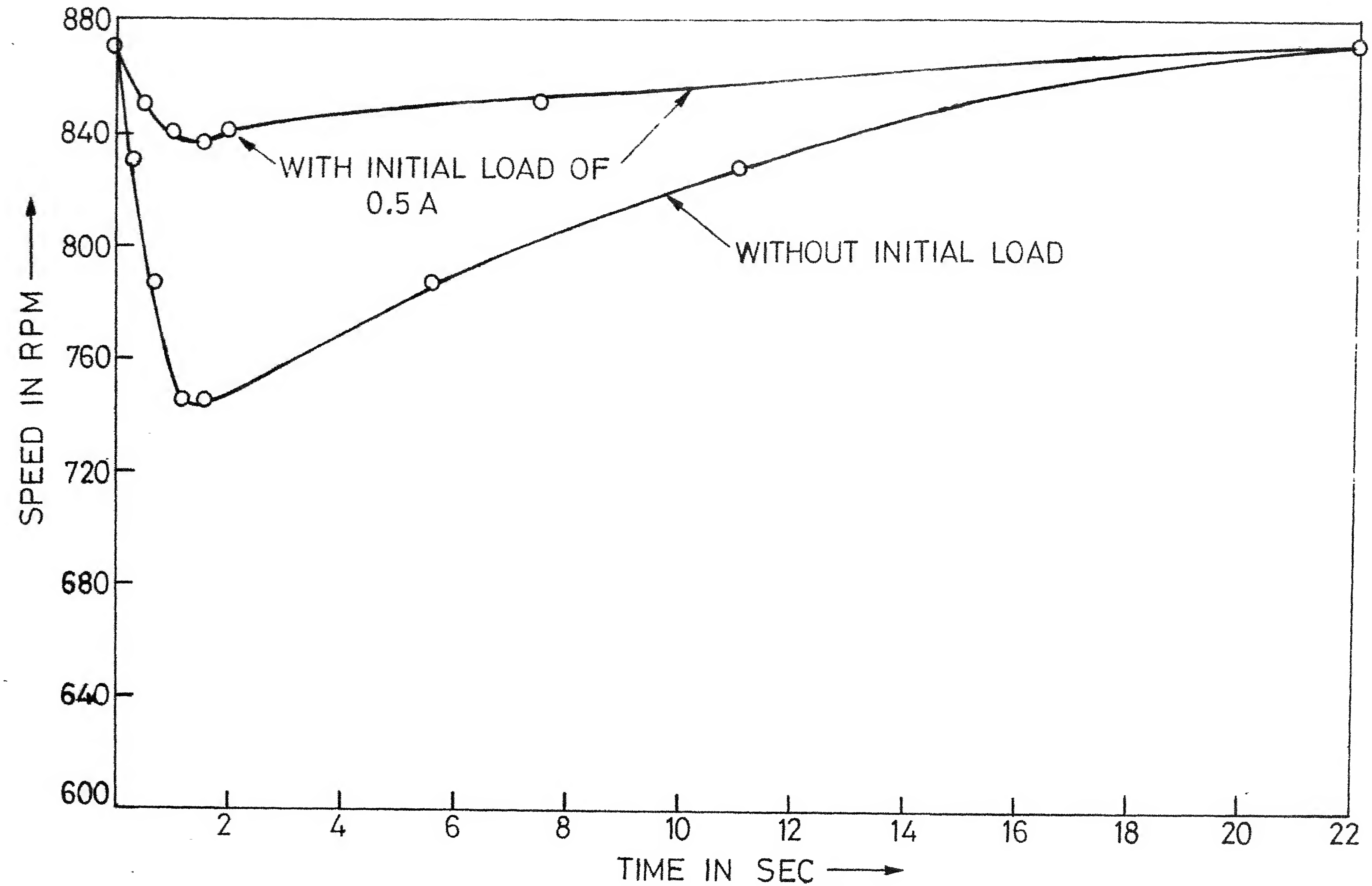


FIG.12 P.I. CONTROLLER WITHOUT CURRENT FEED BACK STEP FRICTIONAL LOAD

4.3.3 Proportional controller with current feed back

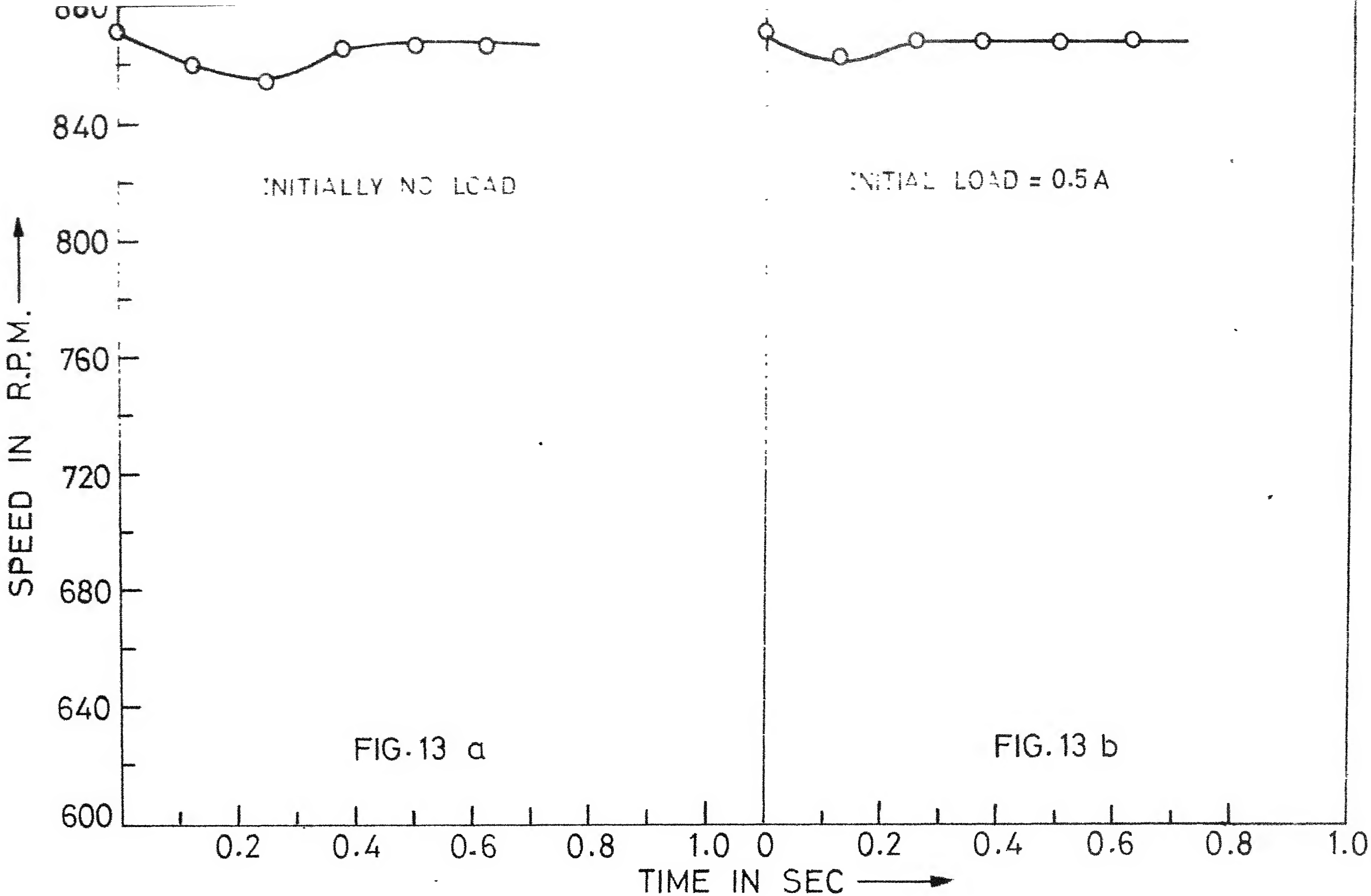
The proportional controller as discussed in Chapter 3 is used with current feed back loop. The experiment is repeated as earlier and the results are tabulated in Table 8 and curves are shown in Fig. 13.

Table 8

Time speed characteristics with proportional controller and current feed back loop

Time in seconds Speed in RPM

Without initial load		With initial load	
Time	Speed	Time	Speed
0	870	0	870
.125	860	.125	860
.25	855	.25	866
.375	865	.375	866
.5	865		
.625	865	.5	866
		.625	866



PROPORTIONAL CONTROLLER WITH CURRENT FEED BACK STEP FRICTIONAL LOAD

4.3.4 Proportional controller without current feed back

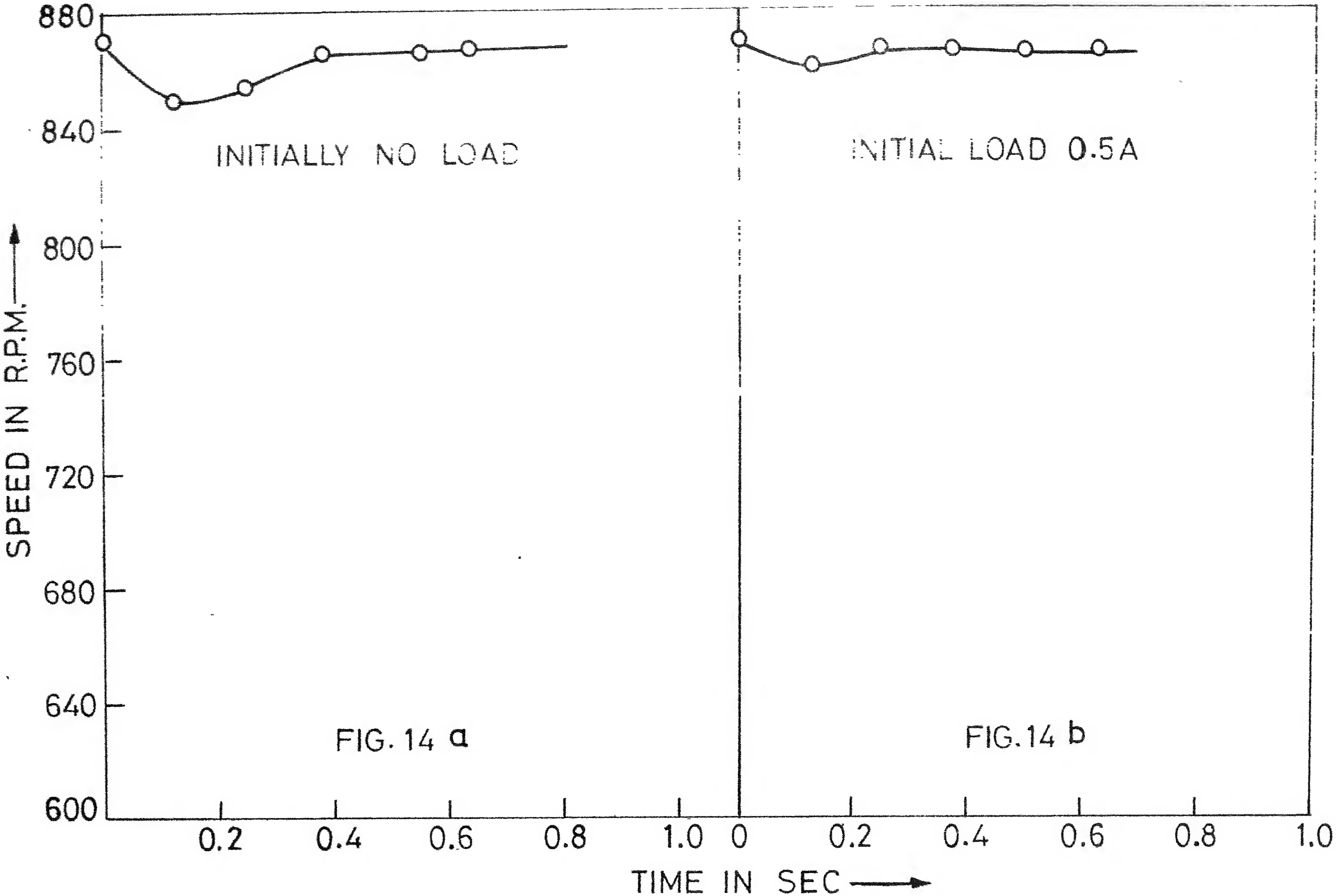
Here the current loop is removed and experiment is repeated, With the same proportional controller. The results are tabulated in Table 9 and curves are shown in Fig. 14.

Table 9

Time speed characteristics with proportional controller without current feed back

Time in seconds Speed in RPM

Without initial load		With initial load	
Time	Speed	Time	speed
0	870	0	870
0.125	850	.125	860
.25	855		
.375	865	.25	865
.5	865	.375	865
.625	865	.5	865



PROPORTIONAL CONTROLLER WITHOUT CURRENT FEED BACK STEP FRICTIONAL LOAD

4.3.5 Open loop control

The two controllers namely speed controller and current controller are removed from the circuit. The firing angle is set at a particular point so that it gives a speed of 870 RPM. Now the load is switched on and plot taken for speed time. The results are given in Table 10 and curves are shown in Fig. 15.

Table 10

Without initial load		With initial load	
Time	Speed	Time	Speed
0	870	0	870
.25	828.57	.25	849.3
.5	787.14	.5	838.6
.75	766.43	1.0	828.0
1.0	745.71	1.5	820.0
1.25	730.0	2.0	814.0
1.5	720.7	2.5	810.0
2	714.7	3.0	810.0
2.5	704.7	4.0	810.0

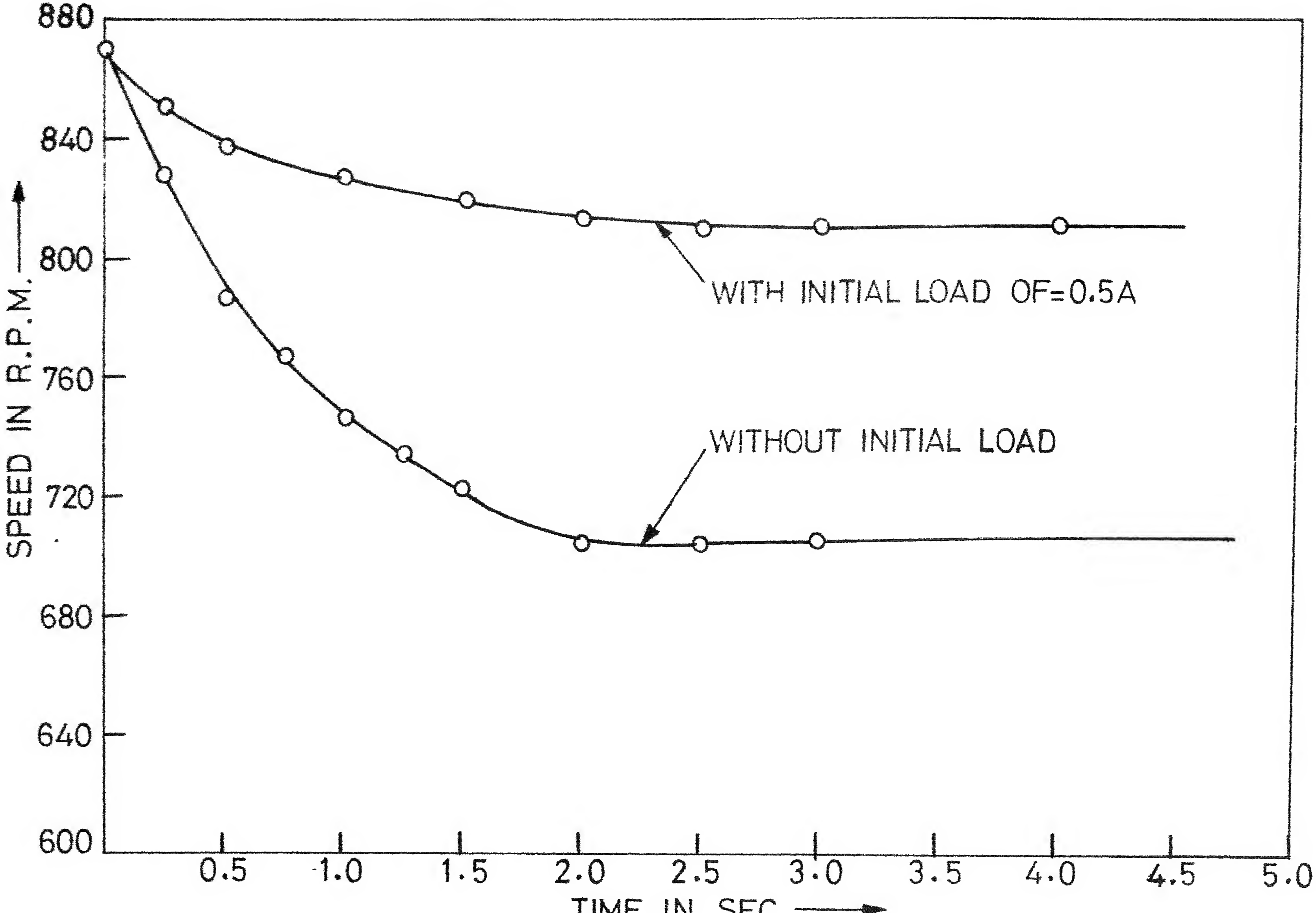


FIG.15 OPEN LOOP CONTROL

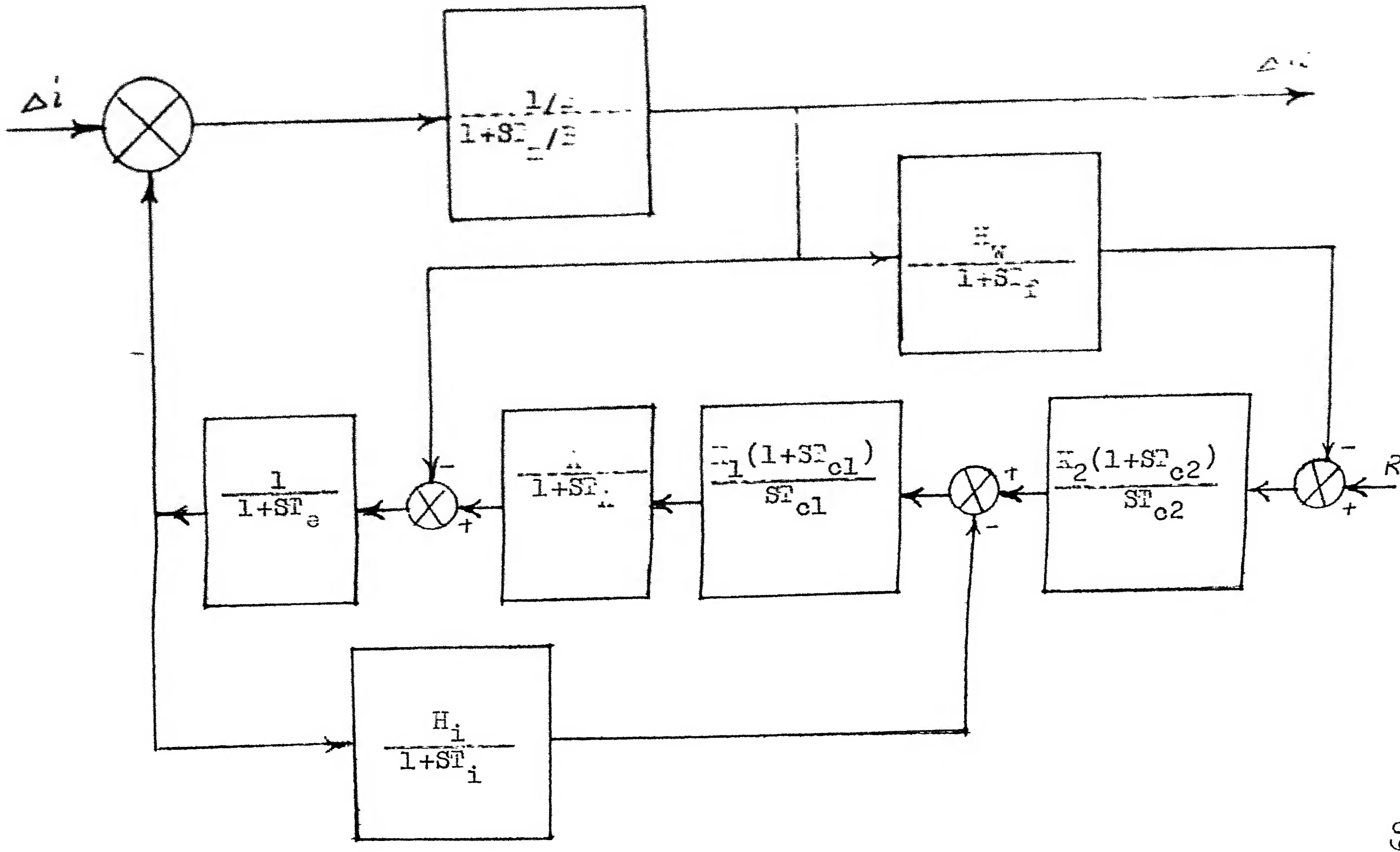


Fig. 16 SYSTEM BLOCK DIAGRAM FOR LOAD PERTURVATION STUDIES WITH CONSTANT TORQUE LOAD

4.4 Computer Simulation

This is done to study the behavior of system when a constant torque load is applied suddenly. As the load is applied it demands more current. Hence to study the step response a current signal i is injected at the error detector Er_4 in Fig. 3. To calculate the transfer function between this current and speed w the diagram is redrawn in Fig. 16. Now the reference R is assumed to be zero for small signal studies and the diagram is again redrawn in Fig. 17.

The transfer function for current loop (Fig. 17) is then calculated which comes to be

$$G_1(s) = \frac{AK_1\ (1+sT_{c1})}{s\ T_{c1}(1+s\ T_e) + AK_1(1+sT_{c1})\ H_i}$$

The poles associated with thyristor amplifier and current transducer H_i are neglected as the associated time constants are very small.

Hence the complete transfer function for feed back loop is :

$$\left(\frac{-H_w\ K_2\ (1+sT_{c2})}{T_{c2}\ s(1+sT_f)} + \frac{-\ sT_{c1}}{A\ K_1(1+sT_{c1})}\right) * \frac{A\ K_1(1+sT_{c1})}{s\ T_{c1}(1+sT_e) + AK_1H_i(1+sT_{c1})}$$

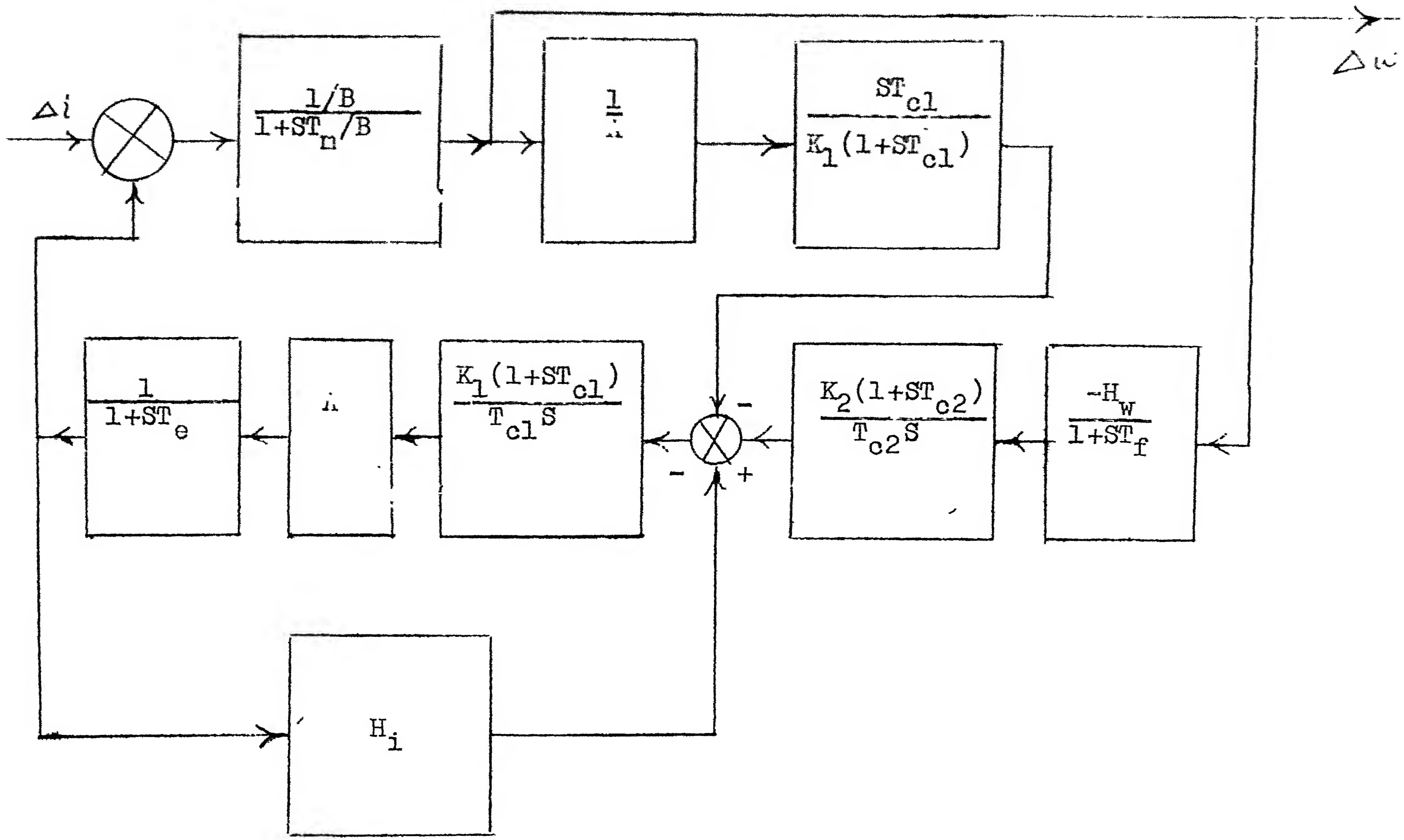


Fig. 17 REDUCED BLOCK DIAGRAM FOR LOAD PERTURVATION STUDIES WITH CONSTANT LOAD

which reduces to

$$-\frac{AK_1K_2\,H_w\,(1+sT_{c2})\,(1+sT_{c1})+s^2T_{c1}T_{c2}(1+sT_f)}{s^2T_{c1}T_{c2}(1+sT_f)(1+sT_e)+A\,K_1\,H_i\,T_{c2}\,s(1+sT_{c1})(1+sT_f)}$$

Hence the complete transfer function

$$\frac{W(s)}{I(s)}=\frac{\dfrac{1/B}{1+sT_m/B}}{1+\dfrac{\frac{1}{B}[A\,K_1K_2\,H_w(1+sT_{c2})\,(1+sT_{c1})+s^2T_{c1}\,T_{c2}(1+sT_f)]}{s^2T_{c1}T_{c2}(1+sT_f)(1+sT_e)+AK_1H_iT_{c2}\,s(1+sT_{c1})(1+sT_f)][1+sT_m/B]}}$$

$$=\frac{\frac{1}{B}[s^2T_{c1}T_{c2}(1+sT_f)(1+sT_e)+AK_1H_i\,T_{c2}s(1+sT_{c1})(1+sT_f)]}{[1+sT_m/B][s^2T_{c1}T_{c2}(1+sT_f)(1+sT_e)+AK_1H_iT_{c2}s(1+sT_{c1})(1+sT_f)]+\frac{1}{B}[A\,K_1K_2H_w(1+sT_{c2})(1+sT_{c1})+s^2T_{c1}T_{c2}(1+sT_f)]}$$

The value of B given in Appendix A is for full frictional load of 2.0 A while in the present investigation the motor is without load and has only inherent frictional losses. Hence the value of B was calculated for no external load and is found to be 0.0428.

After substituting the values of various parameters and simplifying the transfer function becomes :

$$\frac{W(s)}{I(s)} = \frac{9.166s^4 + 169.22s^3 + 873.6s^2 + 1335.37s}{s^5 + 18.84s^4 + 147.153s^3 + 396.4s^2 + 95.244s + 5.2845}$$

The above transfer function is of the form :

$$\frac{W(s)}{I(s)} = \frac{b_1 s^4 + b_2 s^3 + b_3 s^2 + b_4 s + b_5}{s^5 + a_1 s^4 + a_2 s^3 + a_3 s^2 + a_4 s + a_5}$$

Now by dividing the numerator and denominator by s^5

$$\frac{W(s)}{I(s)} = \frac{b_1 s^{-1} + b_2 s^{-2} + b_3 s^{-3} + b_4 s^{-4} + b_5 s^{-5}}{1 + a_1 s^{-1} + a_2 s^{-2} + a_3 s^{-3} + a_4 s^{-4} + a_5 s^{-5}}$$

define

$$E(s) = \frac{I(s)}{1 + a_1 s^{-1} + a_2 s^{-2} + a_3 s^{-3} + a_4 s^{-4} + a_5 s^{-5}}$$

Hence,

$$E(s) = I(s) - [a_1 s^{-1} + a_2 s^{-2} + a_3 s^{-3} + a_4 s^{-4} + a_5 s^{-5}]E(s) \quad (1)$$

and

$$W(s) = [b_1 s^{-1} + b_2 s^{-2} + b_3 s^{-3} + b_4 s^{-4} + b_5 s^{-5}]E(s) \quad (2)$$

Now define the state as the output of each integrator from x_5 to x_1 associated with a_1 to a_5 respectively and writing it in matrix form becomes :

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\\ \dot{x}_5\end{bmatrix} = \begin{bmatrix}0 & 1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 0 & 1\\ -a_5 & -a_4 & -a_3 & -a_2 & -a_1\end{bmatrix} \begin{bmatrix}x_1\\ x_2\\ x_3\\ x_4\\ x_5\end{bmatrix} + \begin{bmatrix}0\\ 0\\ 0\\ 0\\ 1\end{bmatrix} I$$

and

$$W = [b_5 \quad b_4 \quad b_3 \quad b_2 \quad b_1] \begin{bmatrix}x_1\\ x_2\\ x_3\\ x_4\\ x_5\end{bmatrix}$$

Substituting the values of a_s and b_s in the above the equation

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\\ \dot{x}_5\end{bmatrix} = \begin{bmatrix}0 & 1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 0 & 1\\ -18.84 & -147.153 & -396.4 & -95.244 & -5.2845\end{bmatrix} \begin{bmatrix}x_1\\ x_2\\ x_3\\ x_4\\ x_5\end{bmatrix} + \begin{bmatrix}0\\ 0\\ 0\\ 0\\ 1\end{bmatrix} I$$

$$W = [0 \quad 1335.37 \quad 873.6 \quad 169.22 \quad 9.166] \begin{bmatrix}x_1\\ x_2\\ x_3\\ x_4\\ x_5\end{bmatrix}$$

The above equations were solved on computer with i = 0.0055 P.U. The results are given in Table 11 and curve in Fig. 18.

Table 11

Time - speed characteristic for PI controller with current feed back

For constant torque load without any initial load

Time in seconds Speed in RPM

Time	Speed	Time	Speed
0.0	0.0	11.0	-27.3
0.12	-14.37	12.0	-22.995
0.36	-29.7		
0.96	-41.1	13.0	-19.27
1.68	-48.15	14.0	-15.83
2.28	-53.475	15.0	-12.59
3.0	-56.07	16.0	-9.82
3.6	-57.418	17.0	-7.77
4.32	-57.0	18.0	-6.2
4.92	-55 .95		
5.52	-53.8		
6.0	-50.67		
7.0	-46.95		
8.0	-41.97		
9.0	-37.44		
10.0	-31.8		

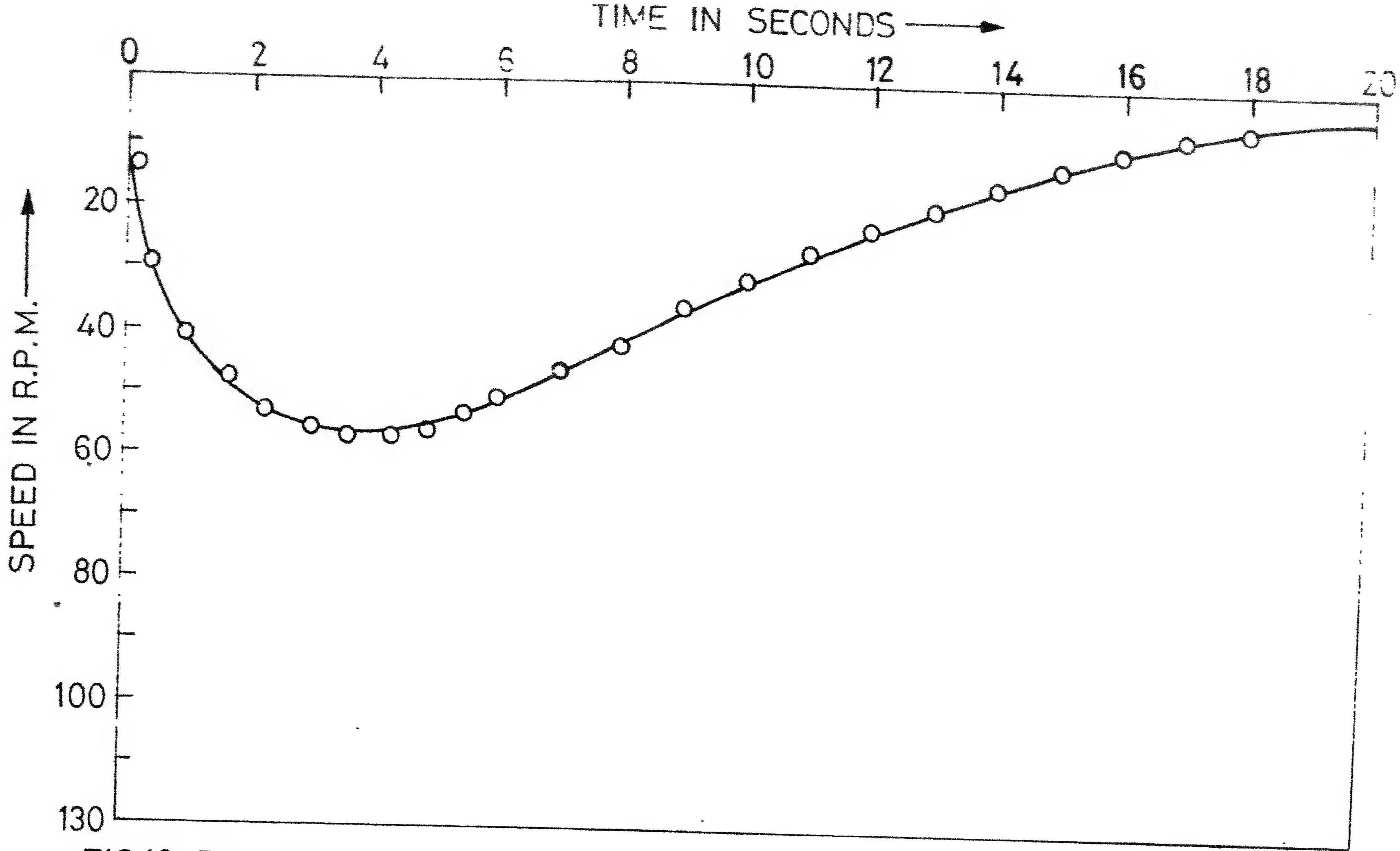


FIG.18 P.I. CONTROLEER WITH CURRENT FEED BACK CONSTANT TORQUE LOAD

4.5 Dynamic Performance with Supply Voltage Change

The PI controller is used for speed loop. The supply voltage is reduced by 20 V suddenly. The experiment repeated with and without current feed back and also with and without initial load on motor. The curves are shown in Fig. 19 and results given in Table 12.

Table 12

Time in seconds Speed in RPM

With current feed back				Without current feed back			
Without load		With load		With load		Without load	
Time	Speed	Time	Speed	Time	Speed	Time	Speed
0	870	0	870	0	870	0	870
.5	880	.5	880	0.5	850	.5	840
1.0	890	1.0	885	1.0	840	1.0	830
2.0	890	2.0	885	2.0	830	2.0	820
3.0	885	3.0	880	4.0	835	4.0	825
4.0	880	4.0	875	6.0	850	10.0	860
5.0	875	5.0	873	10.0	863	15.0	862
6.0	870	6.0	870	14.0	868	18	870
7.0	870	7.0	870	16	870	20	870
8.0	870						

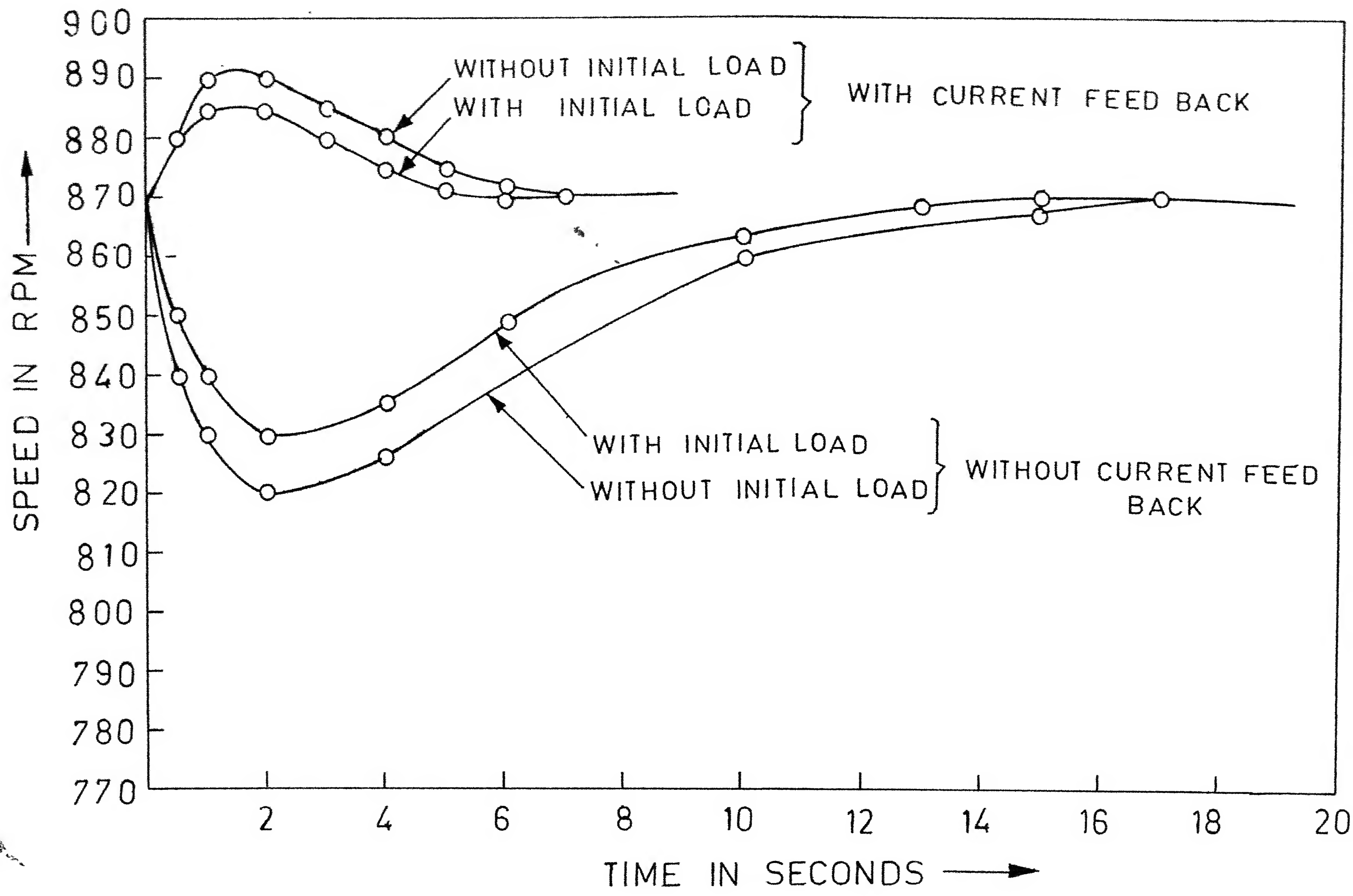


FIG.19: PI CONTROLLER, STEP CHANGE IN SUPPLY VOLTAGE

4.6 Discussion of Results

As seen from Fig. 6 and Fig. 7 the PI controller gives zero steady state error i.e. the speed remains constant with increase in load. While the proportional controller (Figs. 8 and 9) produces some drop in speed as the load is increased, of course in very small amount and can be further improved by increasing the gain of controller. However, the system produces highest regulation in open loop control (Fig. 9) which may not be acceptable for most of the applications. It is observed that there is no effect of current feed back on steady state behaviour of system.

The dynamic behaviour of the system with PI controller with current feed back can be seen in Fig. 11 and Fig. 18. PI controller produces large speed dips whenever the load is applied suddenly. However, if initial load is present it smooths out the dip as shown in Fig. 11. The Fig. 12 and Table 7 give the performance of PI controller without current feed back. The speed dip produced by PI controller with current feed back is more than PI controller without current feed back. The time taken to recover the set speed is same in both the cases. Of course, the load has got the smoothing effect here also. The main advantage of the current loop is to provide better and

faster response when the supply voltage changes as shown in Fig . 19 .

Fig. 13 and Fig. 14 show the behaviour of proportional controller with and without current feed back, with and without initial load. It is clear from the graphs that the speed dips are very small and system recovers to steady state with in a fraction of second. However, there is hardly any effect of current feed back.

Fig. 15 shows the behaviour of system on open loop. With step load. The motor comes to steady state slowly and runs at a much lower speed. Though there is no speed dips the new steady state speed is much below the previous one. It takes more time to come to steady state than proportional controller but is still much less than PI controller.

The lowest speed at which the motor can be run satisfactorily is observed to be 16 rpm while the highest is 1500 RPM giving the control over 1:93 speed ratio. The reversing and inching operation is also seen to operate satisfactorily.

4.7 Conclusion

Where frequent load switching is required and certain amount of regulation (very small) is tolerable the proportional controller with current feed back is a better choise than PI controller. However, if zero steady state error is desired and either there is no switching of load or speed dips are tolerable the PI controller can be used. Open loop controller is not good from the system performance point of view.

APPENDIX A

CALCULATION OF MOTOR PARAMETERS

(i) The armature resistance and inductance was measured by an impedance bridge and was found to be :

$$R_a = 5.6 \text{ ohms}$$

$$L_a = 55 \text{ mH}$$

(ii) To calculate the moment of inertia constant 'J' retardation test was performed. The motor is run at rated speed of 1500. The power losses is noted by measuring the power input to motor and subtracting the copper loss. Now the supply is switched off and the fall of speed V/s time is recorded on a recorder. The reduction in speed is assumed to be due to friction only. From the knowledge of frictional loss at full speed, choosing a point on the curve the losses are calculated. The $\frac{dw}{dt}$ is calculated from the curve. Hence J is given by the formula

$$\frac{dw}{dt} = \frac{P}{WJ}$$

J was calculated at several points and a mean value is taken to be 9.13×10^{-3}. Nw.m^2.

(iii) The motor is run as generator and a emf v/s speed curve is plotted from this curve the back emf constant (given by $E_b = K_b W$). K_b is calculated to be 1.4 V/rad/s

Since one similar motor is connected as load on the motor the frictional constant f is calculated from the knowledge of K_b.

Since the torque $T = fw$

$$\text{and } T = \frac{E_b I_a}{W} = \frac{K_b W\ I_a}{W}$$

where W is rated speed and I_a the full load current of motor (2.0 A).

$$f = \frac{2\ K_b}{W} = 1.782 \times 10^{-2}$$

Hence $\frac{T_m}{B} = \frac{9.13 \times 10^{-3}}{1.782 \times 10^{-2}} = 0.513$ sec.

where T_m is mechanical time constant, and B is frictional feedback constant given by Torque = BW.

(iv) To calculate the constant B. The torque V/s speed characteristic of the motor is found experimently. From the relation :

$$(\text{Torque})\ T = BW$$

the value of B is calculated and normalized, it works out to be 0.214.

Hence the mechanical time constant

$T_m = 0.513 \times 0.214 = 0.1098$ sec.

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